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INTERIM FIELD EVALUATION OF WINDROW REVETMENT, MISSOURI RIVER, --ETC(U)
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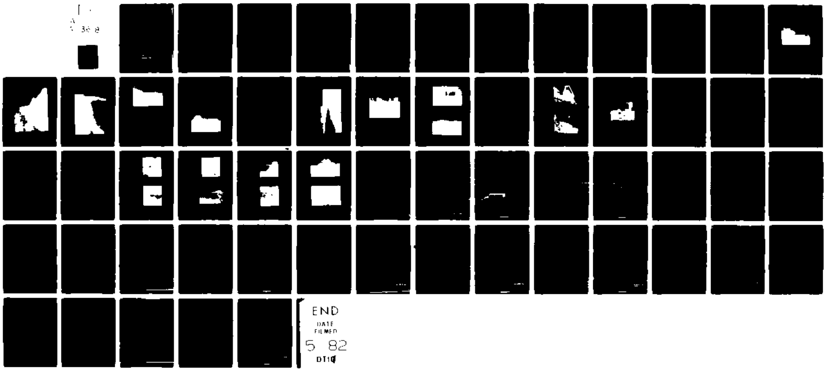

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MISSOURI RIVER
SECTION 32
STREAMBANK EROSION CONTROL

INTERIM FIELD EVALUATION OF WINDROW REVETMENT

United States Army
Corps of Engineers
...Serving the Army
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Omaha District

MARCH 1980

INTERIM FIELD EVALUATION OF WINDROW REVETMENT

Streambank Erosion Control Evaluation and Demonstration Program

U. S. ARMY ENGINEER DISTRICT, OMAHA

U. S. ARMY CORPS OF ENGINEERS

OMAHA, NEBRASKA

PREFACE

The objective of this report is to describe and evaluate the performance of a low cost, environmentally acceptable erosion control technique called windrow revetment. The structure was designed, constructed, and monitored by the Omaha District, U. S. Army Corps of Engineers on the left bank of the Missouri River near Vermillion, South Dakota.

The project evaluation was conducted under the general supervision of Omaha District Personnel: Mr. L. Horihan, Mr. H. Christian, and Mr. F. Vovk. The field investigation and project evaluations were conducted by Omaha District personnel Mr. R. Singleton and Mr. B. Berry. The model investigations were conducted from February 1972 to July 1974 by Omaha District personnel Mr. R. Singleton, Mr. E. Matson, and Mr. W. Howard. This report was prepared by Mr. B. Berry.

A

TABLE OF CONTENTS

LIST OF PHOTOGRAPHS

LIST OF PHOTOGRAPHS

LIST OF PLATES

CONVERSION FACTORS

The units of measurement customarily used in the United States and used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
Inches	0.02540	Meters
Feet	0.3048	Meters
Square Feet	0.092903	Square Meters
Feet Per Second	0.3048	Meters Per Second
Cubic Feet Per Second	0.028317	Cubic Meters Per Second
Fahrenheit Degress	5/9	Celsius Degrees or Kelvins*
Tons	0.9078	Tons (Metric)
Tons/Lineal Foot	2.97835	Tons (Metric)/Meter

*To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F-32) + 273.15$.

MISSOURI RIVER NEAR THE VERMILLION RIVER CHUTE, SOUTH DAKOTA

WINDROW REVETMENT PERFORMANCE REPORT

I. INTRODUCTION

A. Project Name and Location. Vermillion River Chute Area - Missouri River Mile 771, near Vermillion, South Dakota. Plate 1 shows a location map of the study area.

B. Authority. Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251.

C. Objective. To describe and evaluate the performance of low cost environmentally acceptable erosion control technique designed, constructed, and monitored by the Omaha District, U. S. Army Corps of Engineers. This report concerns the performance of a windrow revetment structure placed along the left bank of the Missouri River near Vermillion, South Dakota.

II. MISSOURI RIVER STUDY REACH DESCRIPTION

A. Missouri River Flow Regime. The amount of flow in the Missouri River is totally controlled by six upstream mainstem dams and reservoirs with the Gavins Point Dam being the most downstream control point. The probability of the demonstration site study reach experiencing any flood flows exceeding bank full capacity is remote.

The releases from Gavins Point Dam have practically no sediment load; therefore, the accretion of new high elevation land through the deposition of sediment in the demonstration site study area is highly unlikely. The river begins to pick up sediment from the river's channel bottom and banks as soon as it leaves the Gavins Point Dam approximately 40 river miles upstream from the study reach. The tributary streams between Gavins Point Dam and the study reach add an insignificant amount of sediment load to the Missouri River.

At present, the bars and sediment deposits on the channel bottom shift with time. Considering the above river conditions and review of periodic aerial photography, it is evident the channel will continue to widen and degrade rather than accrete in the demonstration site study area.

B. Geology. The study area lies in the physiographic province of the Missouri Valley. The rock formations which are exposed in the Missouri Valley belong to three geologic systems: the Quaternary, Tertiary, and Cretaceous (Ref. 1).

The sediments associated with the study reach are the Pleistocene formations of the Quaternary period. The Pleistocene formation is composed primarily of alluvium, loess, and glacial drift. Alluvial deposits composed of clay, silt, sand, and some gravel make up the floor of the Missouri Valley on which the rivers flow and include flood plain deposits. See Figure 1.

The age of the Missouri River dates back to the Pleistocene epoch; consequently, a deposit of alluvium approximately 70 to 185 feet thick has been laid down in the valley (Ref. 1).

The surface of the alluvial deposits is generally flat to undulating. The islands and sand bars in the river are composed of alluvial deposits. On the whole, the rich alluvium in the Missouri Valley supports abundant natural vegetation and agricultural crops.

C. Climate. The seasonal distribution of rainfall typical of the study area is classified as dry subhumid. As is typical of an interior plains of the United States, the deviation from climatic norms from year to year is very great. The winters are long and cold and the summers are short and relatively hot. The maximum precipitation occurs in early summer when moisture from the Gulf of Mexico is transported into the region by prevailing southerly winds. The winter precipitation, chiefly in the form of snow, is considerably less because of the decreased moisture carrying ability of the colder air masses and small quantity of moisture in the prevailing northwest winds. Approximately 45 percent of the annual precipitation occurs in the three summer months whereas only 10 to 15 percent occurs in the four driest months, November to February. Excessively high and low temperatures are characteristic of the study area. Maximum temperatures in excess of 100°F have been experienced, while temperatures below 0°F are common during the winter season.

D. Discharge Data. The recorded peak instantaneous discharge for the Missouri River at Yankton, South Dakota, is about 480,000 c.f.s., which occurred on 13 April 1952; the minimum flow of record is about 2700 c.f.s. and occurred on 10 January 1940 and also 15 and 16 November 1940 (Ref. 4). These discharge measurements were made during and shortly after construction of the first mainstem dam, and, therefore, the river at that time was considered to be uncontrolled. The range of expected discharges now is 15,000 to 80,000 c.f.s. The Gavins Point Dam 100-year release is 80,000 c.f.s.

III. DEMONSTRATION SITE - TEST REACH

A. Riverbank Materials. The materials which make up the channel banks and valley floor of the Missouri River valley are alluvial deposits composed of clay, silt, sand, and some gravel. See Figure 1.

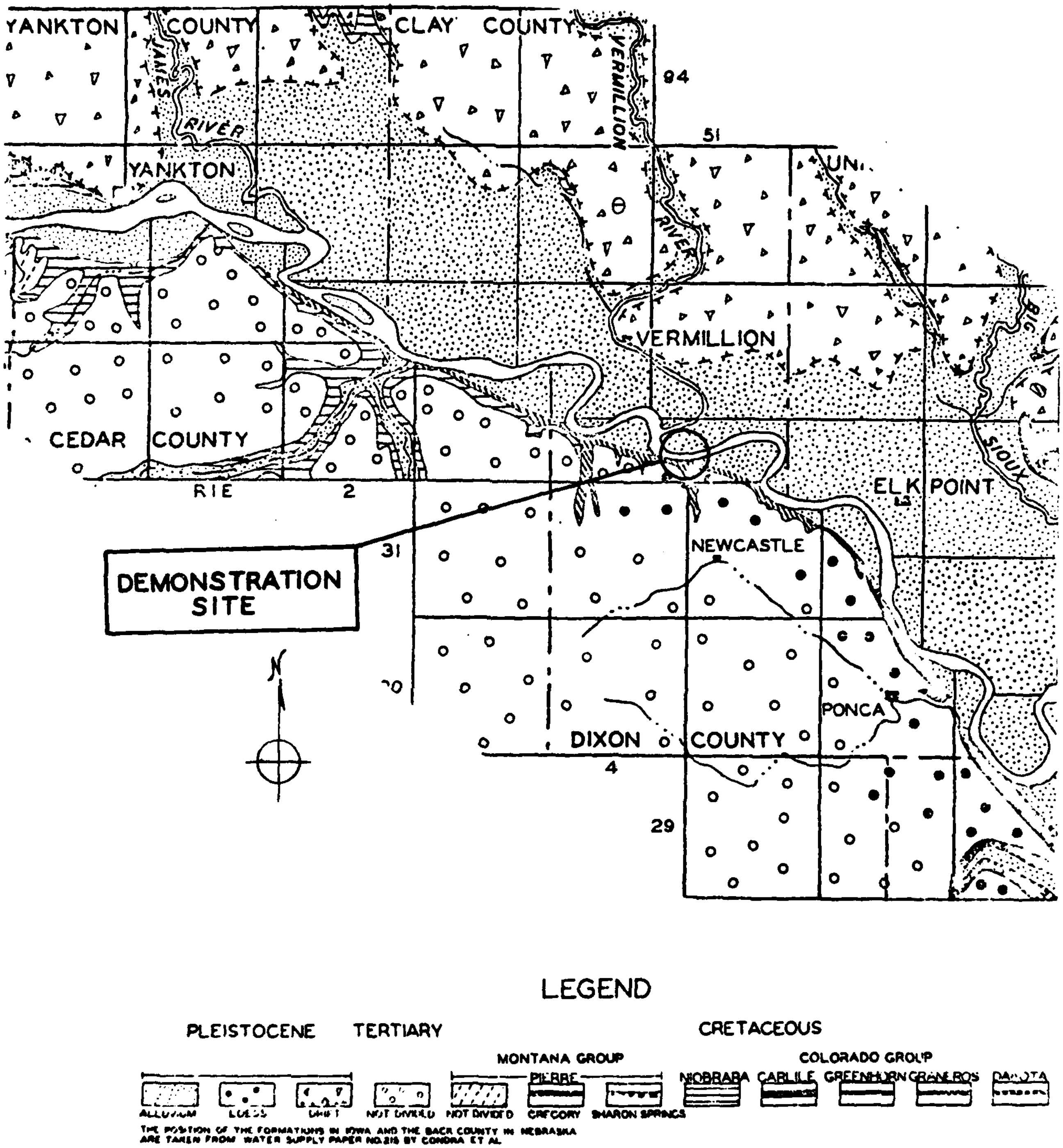


Figure 1. Geologic Systems of the Demonstration Site Study Reach (Ref. 1).

Since landowners around the test reach are no longer confronted by the problems of periodic flooding, the land has been put to more extensive and productive agricultural use. The continuation of erosion without control measures to halt the land losses, reduces the income for the landowners and adversely affects the general economy of this agricultural area.

B. Normal Bank Vegetation. The vegetative cover on the edge of the left bank of the Missouri River in the study area consists almost entirely of native grasses. See Photograph 1.

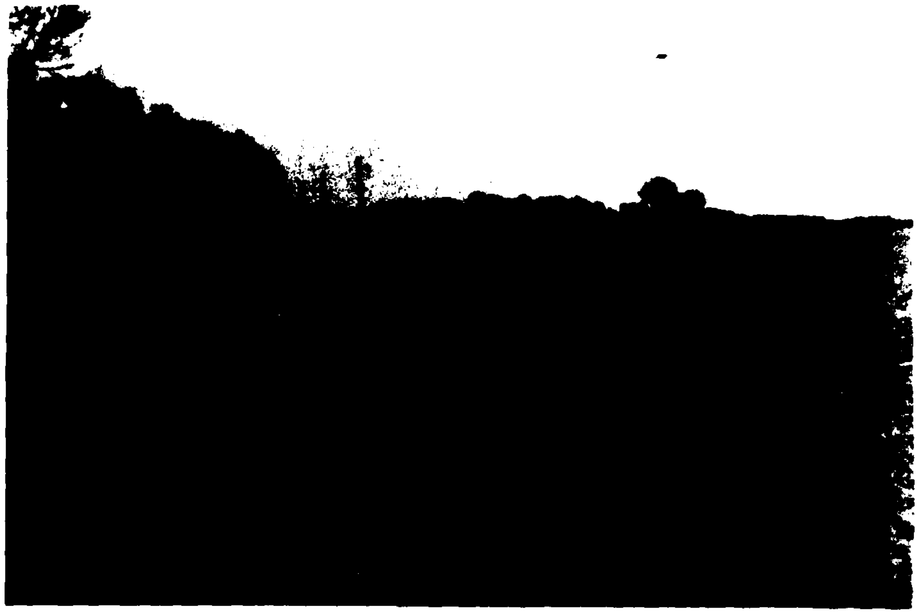
Photograph 1. View of farm land immediately adjacent to the windrow between Stations 30+00 to 35+00. Date: 29 May 1979

The landowners have removed nearly all the trees from the study area and have converted the land to agricultural use. The right bank in this area has a dense growth of cottonwood and willow trees, heavy brush, and many other types of trees which are indigenous to the Vermillion area. Between the edge of the high left bank and the water's edge, very little vegetation is present because of the high rate of bank erosion. See Photograph 2.

Photograph 2. Typical view of channel bank prior to placement of the windrow revetment.
Date: May 1977

C. Bank Topography. The surface of the alluvial deposits along the Missouri River is generally flat. A typical comparison of the test area between the edge of the upper bank and the edge of the water before and after placement of windrow revetment is shown in Photographs 3 and 4.

Photograph 3. Downstream view of demonstration site study reach prior to construction of the windrow revetment. Date: Jan 1977



Photograph 4. Downstream view of demonstration site study reach.
Date: 29 May 1979

The difference in elevation between the edge of the upper bank and the normal water surfaces is approximately 20 feet as can be observed in both photographs 3 and 4.

D. Hydraulic Characteristics. The test reach was monitored at various times from 1976 through 1979. The 1976 survey was made prior to the start of construction activities. Three tasks accomplished during this survey were as follows:

1. Sufficient flow velocity measurements were taken in the channel to plot the velocity distribution.

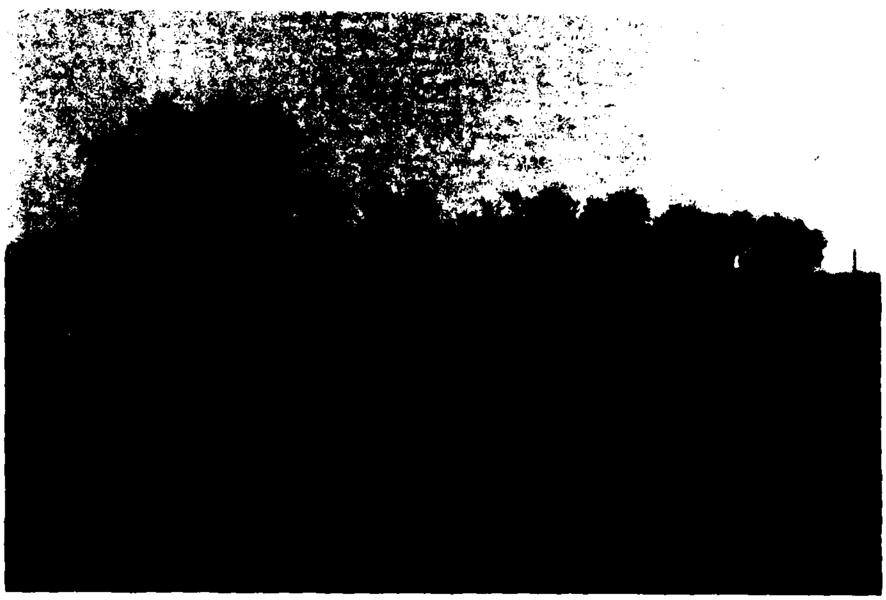
2. Cross-sections were surveyed.

3. Photographs were taken.

These same tasks were also performed in 1977 for the second survey. During that survey, the rock size distributions of the windrow and the bank paving areas were also determined at four sites along the revetment. The sampling procedure is described in Section VI-B of this report. During the third and fourth surveys in 1978 and 1979, the tasks performed in the 1976 survey were repeated. Detailed measurements were taken in the test reach before and after placement of the windrow revetment to observe the influence of the windrow on the hydraulic characteristics of the test reach. The discharges in the Missouri River at the time of these measurements ranged from 28,100 c.f.s. to 37,150 c.f.s. Plates 5 through 9 show velocity distribution at various locations along the test reach.

The maximum velocities observed along the reach were 5.3 f.p.s. before and 4.8 f.p.s. after the placement of the windrow revetment. A discharge rating curve for the study area is shown on Plate 4.

E. Channel Conditions. The existing channel along the test reach is braided. Currently the main flow is located along the left bank which causes higher velocities in that portion of the channel and, in turn, results in increased erosion rates along the channel bank. The banks in this reach of the river are easily erodible. The river width increases at high flows and sand bars appear at low flows. The smaller channels and sand bars change position with time and river stage. The left edge of the island which is located across the main channel from the study reach has received some erosion during the monitoring time and, along the windrow revetment, the channel has tended to deepen especially along the downstream portion. The island splits the flows of the Missouri River. As of 29 May 1979, and as shown on Plate 9, the left channel adjacent to the study reach carried 72 percent of the total discharge in the river. This is important because flows of the river could transfer to the right channel area and result in future reduction of flows along the test reach in the left channel. The channel has begun to shoal at a location approximately one river mile downstream of the test site.



Photograph 5. View of Windrow Revetment from the main channel of the Missouri River. Date: 29 May 1979

IV. DESIGN AND CONSTRUCTION

A. General. The windrow revetment method of bank stabilization appeared to provide the most viable means of protecting adjacent farm land from continued erosion loss. No previous attempts at bank stabilization had been made in this particular reach of the Missouri River. This test site was one of the first windrow revetments constructed by the Omaha District on the "open" Missouri River reach between Gavins Point Dam and Ponca State Park, Nebraska. This windrow application consisted of (1) a trench excavation along the top of the high bank parallel to the river channel (2) graded fieldstone placement in the trench (3) covering the fieldstone with a shallow layer of soil, and (4) reseeding the area of the excavation. Any stone material could be used for the windrow as long as it meets standard design criteria of size and weight. Fieldstone was used here because it was readily available from local sources.

B. Basis for Design. The primary reasons for selecting the windrow revetment method of bank stabilization were the ease of construction and the unusually large channel bank area which was exposed both above and below the water surface. The water depths were approximately 20 feet immediately adjacent to the channel bank and the channel banks also extended about 20 feet above the water surface. This condition would have made any other protection technique very expensive. The upper bank of the test reach, which is composed of an alluvial deposit, is relatively flat. Therefore, the excavation of the revetment trench, which was 16± feet wide and 6± feet deep, was easily accomplished. The windrow was constructed from river bank stations 25+00 to 45+70, for a total length of 2070 feet. A total of approximately 9645 tons of upper bank excavation was required. Graded fieldstone from local sources was then placed into the excavation. The total amount of fieldstone which was used in the original test reach was 9321 tons. This number reduces to a figure of about 4.5 tons/lineal feet of bankline. The site modification which required additional excavation and placement of additional fieldstone is described in Section V of this report. A shallow layer of topsoil was then placed on top of the windrow rock to aid the growth of native vegetation and restore the natural appearance to the upper bank area. As the river cut the bank away, the fieldstone from the windrow dropped into the river. The amount "fed" onto the lower bank varied with the amount of erosion which occurred along the lower bank. Photograph 6 shows a view of the windrow revetment immediately after construction. The addition of stone to the original windrow in the lower portion of the test reach has been necessary because of the concentrated channel velocities and greater than anticipated scour depths.

C. Cost. The total cost of materials, labor, and installation of the original windrow revetment amounted to $106,665 or approximately $42 per lineal foot of channel bank line.

V. SITE MODIFICATIONS

A. General. It was necessary in 1978 to provide additional fieldstone in an area where the original fieldstone placed in the windrow

Photograph 6. Upstream view of windrow revetment immediately after construction.
Date: 17 May 1977.

had been used. The additional stone was needed to insure continued protection of the upper portion of the revetment blanket. This material was needed to repair the bank between stations 41+70 and 45+45. The repair consisted of an upper bank excavation of 800 cubic yards of soil approximately 4 feet deep and 8 feet wide. A total of 576 tons of fieldstone obtained from local sources was placed into the excavation. This is approximately 1.5 tons/lineal foot of additional stone placed in the windrow.

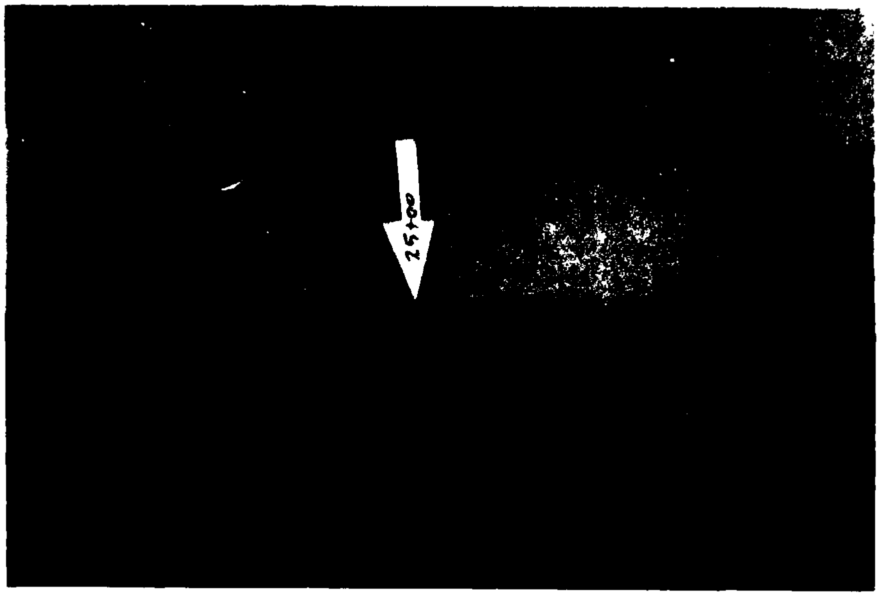
B. Cost. The total cost of this modification to the study reach was $9,430 or approximately $25 per lineal foot of bank line.

Photograph 7. Typical view of windrow revetment, Date: 29 May 1979

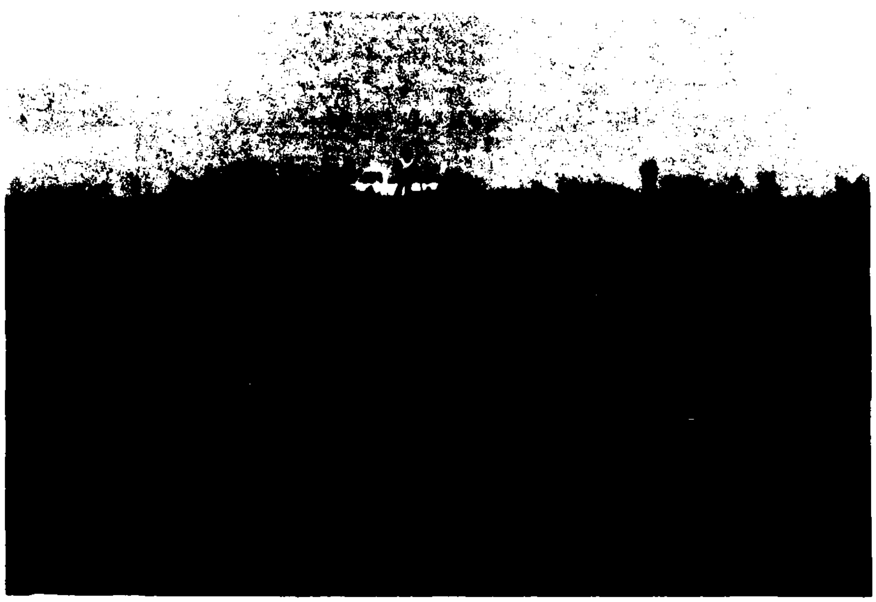
VI. PERFORMANCE OF PROTECTION

A. General. The windrow revetment in the Vermillion River Chute area has been monitored for two reasons. First, in accordance with Section 32 directives, to evaluate the performance of this method for streambank erosion control. Second, to obtain field data which would aid in verifying laboratory model studies of windrow revetment conducted at the U. S. Army Corps of Engineers Mead Hydraulic Laboratory near Mead, Nebraska. Initial field measurements were made of the windrow revetment on the second and third of December 1977 (approximately six months after construction was completed). At this time, the measurements consisted of bank line cross sections, measuring flow velocities and discharges, obtaining photographs, and monitoring rock gradations. Sampling was done at that particular time to take advantage of the low flow conditions which exposed a large section of the windrow revetment.

The revetment rock sampling was limited to four sites located between station 25+00 and station 44+00. The sites were selected by the



Photograph 8. View of upstream end of windrow revetment. Date: 29 May 79



Photograph 9. Close-up view at Station 25+00. Date: 29 May 1979

contracting officer at locations where the windrow revetment had sufficiently developed to provide a protective armament along the lower bank. Station 25+00 is shown in Photographs 8 and 9.

B. Revetment Sampling Procedure. The first step in the revetment sampling procedure was to locate each sampling test site and tie them in with the existing bank stationing. At each sampling site, a centerline perpendicular to the channel bank was established. A complete cross section was taken, starting 50 feet landward from the edge of the high bank and extending riverward along the test section centerline to the water's edge and then continuing across the river channel to the edge of the far island.

Each sampling site consisted of two areas, (a) the noneroded upper bank windrow and (b) the windrow revetment. Samples were extracted from the windrow and from the exposed revetment. See Plate 3. The upper bank windrow pertains to that noneroded area in which the initial windrow rock remained. The term windrow revetment refers to the protective armament formed by the fieldstone from the upper bank windrow which has fallen onto the lower bank.

The size of the sampling area was determined such that the sample would be representative of that area for that size stone. The windrow revetment sampling area was rectangular in shape, bounded on two sides by lines running parallel to and located nine feet upstream and downstream from the established test site centerline. The other two sides of the windrow revetment sampling area were located by lines which were perpendicular to the established centerline, one located about one foot riverward from the toe of the upper bank and the other coinciding with the water's edge.

The corners of each sampling area were temporarily marked using stakes with orange flags. Partial cross sections of the windrow revetment sampling area were obtained on lines parallel to the established centerline and were spaced at three foot intervals over the entire length. The windrow revetment sampling area layout is shown on Plate 3.

All of the stone in the sampled areas were excavated with a minimal amount of disturbance to the underlying bank. The equipment used to remove the stone from each sampling area is shown in photograph 10.

Photograph 10. View of equipment removing a sample of the windrow revetment. Date: 2 Dec 1977

Photograph 11. View of windrow revetment after samples had been removed. Date: 2 Dec 1977

All of the excavated materials were saved and tested in the following sequence:

1. Sample was washed in river then dumped on the bank.

2. The stone was hand sorted by size. See photograph 12.

3. Largest size was loaded into dump truck and weighed.

4. Next smaller sizes were added and weighed until all sizes were weighed.

Photograph 12. View of sampled stone which had been sorted by hand with respect to size. Date: 2 Dec 1977

After the test measurements and the weighings of the stone of the lower bank material was completed and recorded, the stone was placed back onto the lower bank location and dressed to reasonably smooth lines and existing grades. The stone from the original windrow within the test site limits was sampled in a similar manner.

C. Velocity Measurements. Velocities through the test reach were measured at the hydrographic range locations once prior to and three times subsequent to construction of the windrow. These locations are shown on Plate 2. The results of these measurements are shown on Plates 5 to 8. A graphical view of average velocity trends along the reach are shown on Plate 9.

D. Project Time Frame. Table 1 shows the time of events concerning this demonstration project.

TABLE 1. DAY OF EVENTS

Event	Started	Completed
1. First Survey*	10 Nov 76	11 Nov 76
2. Original Construction	15 Feb 77	14 May 77
3. Second Survey*	19 Sep 77	20 Sep 77
4. Sampling of bank paving	2 Dec 77	3 Dec 77
5. Revetment Modifications	22 Aug 78	3 Nov 78
6. Third Survey*	11 Sep 78	14 Sep 78
7. Fourth Survey*	29 May 79	29 May 79

*Survey included cross sections, velocity measurements, etc.

E. Environmental Considerations. This bank stabilization method did not have any apparent adverse effect on the wildlife of the study area. The vegetation which is growing on the top of the upper bank and on the revetment slope has improved the wildlife habitat and also provides the wildlife with an additional food source. The stabilized bank also reduces the amount of sediment entering the river from bank erosion but for this short reach the effect is negligible on the water quality of the Missouri River. The channel bank along the study reach would appear to be in a natural state by the casual observer. By letting the river provide the mechanism for placing the windrow stone on the bank slope, the disturbance to the ecology of the study area is kept at a minimum.

F. Results. The results of the velocity measurements taken during the four years are shown on Plates 5 through 8. A non-dimensional summary of velocities taken from Plates 5 through 8 is shown on Plate 9. As the windrow revetment developed, the bank line along the study reach became more uniform. This more uniform bank line is believed to have resulted in a reduced roughness coefficient (n value). The reduced resistance coefficient combined with the fact that the flow is also forced toward the left bank by the bend has resulted in increased velocity concentrations adjacent to the left bank as shown on Plate 9. The increase in scour along the study reach is also believed to be directly related to this increased velocity.

The rock size distribution curves are shown on Plate 10. The plot of the composite rock size distribution curve is shown on Plate 11. The difference between the windrow curve and the windrow revetment curve would appear to indicate that when the rock from the windrow falls upon the lower eroding slope, some of the smaller diameter material is removed by the tractive force of the water flowing along the revetment. Some loss can also be attributed to the sampling process of washing the sample. This can also be seen by studying the rock application shown in Plate 12.

The changes in the configuration of the left channel bank along the study reach is shown on Plate 13. At nearly all the stations shown on this plate, degradation has occurred since construction of the project. The reduction in bank erosion is shown by comparing the vertical distances between the cross-sections of each year on the same graph. Hydrograph ranges 4 and 6 show almost no lateral erosion between 1978 to 1979.

G. Windrow Model Study Comparison. Model studies conducted at the Mead Hydraulic Laboratory indicate that the integrity of the windrow revetment depends on the amount of coverage provided by the individual stones. Coverage is best expressed by porosity, η. The better the coverage, the less porous the revetment will be. Mead model studies have shown the revetment porosity may be related to the dimensionless parameter, $\frac{W/A}{d\gamma}$, where:

W/A = weight of stone in windrow or in revetment over a unit area

d = maximum stone diameter of gradation

γ = unit weight of stone

The model studies have also shown that the parameter, $\frac{W/A}{d\gamma}$, up to a value of 0.6, is directly proportional to $1-\eta$. The value of 0.6 represents the maximum density of a single layer thickness equal to the maximum stone diameter.

Within the range of normal revetment thickness, the parameter $1-\eta$ increases only slightly with a maximum value being about 0.68 for a $\frac{W/A}{d\gamma}$ value of 1.5. To insure adequate coverage, the value of $\frac{W/A}{d\gamma}$ for the revetment should be greater than 0.6.

The respective values associated with the data collected from the Vermillion River Chute windrow revetment are shown in Table 2.

TABLE 2 DEMONSTRATION SITE REVETMENT PARAMETERS			
RANGE	$\left(\frac{W/A}{d\gamma}\right)_A$	$\left(\frac{W/A}{d\gamma}\right)_B$	$\left(\frac{t}{d}\right)_B$
4	0.65	0.51	1.03
5	1.03	0.50	1.22
6	0.65	--	--
7	0.72	0.72	1.32
8	0.96	0.36	0.67

SUBSCRIPT DESIGNATION

A - *refers to the total stone coverage* from the revetment toe up to bottom of high bank (estimated).

B - refers to the stone coverage in the sampled revetment areas only (measured samples).

The values shown in the $\left(\frac{W/A}{d\gamma}\right)_A$ column of Table 2 are all greater than the 0.6 which indicates that the windrow revetment, in general, should provide adequate coverage to prevent further erosion of the left bank. However, the computation of this parameter assumes that the blanket thickness, t, of the revetment, is uniform along the entire slope. The data in the $\left(\frac{W/A}{d\gamma}\right)_B$ column of Table 2 contains values less than 0.6 which indicates that uniform blanket thickness assumption is not entirely valid. The values which are less than 0.6 indicate that there is not a sufficient amount of stone in the upper portion of the revetment blanket to ensure adequate coverage. Therefore, based on laboratory analysis, erosion is likely to continue along the upper portion of the revetment until a sufficient amount of the windrow rock is "fed" onto the revetment slope to provide adequate coverage. The Range 8 value indicated the need for more stone and subsequently more had to be added. The values shown in the $\left(\frac{t}{d}\right)_B$ column of Table 2 represent the ratios of the sampled blanket thickness to the maximum stone diameter of gradation. These values indicate the upper blanket thickness in rock diameters.

H. <u>Evaluation of Protection Performance.</u> The objective of using windrow revetment at this particular site on the Missouri River was to test the performance of this type of revetment under extreme conditions and to prove that it could be a low cost environmentally acceptable erosion control technique. These extreme conditions consisted of a 20-foot near vertical drop from the top of the left high bank to the water surface (see photograph 2) and water depths of approximately 20 feet immediately adjacent to the left channel bank. These conditions would have made any other erosion control technique more hazardous to install than windrow revetment since implementation of the windrow method requires work only at a safe distance back from the edge of the high bank.

The advantages of using a windrow revetment are:

1. Complex site preparation is not required and minimal disturbance to the natural bank results in less construction time requirements.

2. Manipulation of the stone is reduced to a minimum.

3. Excess stone may be salvaged from the windrow and used somewhere else after adequate coverage of the protected slope has been provided. (Maximum quantity optimization)

4. Hazardous sites may be protected without risking the safety of the personnel installing the protection.

5. Volunteer vegetation on the stabilized revetment bank provides an excellent wildlife habitat and food source. (Aesthetic and environmental benefit).

Over the period of time since construction of this windrow, the left bank has undergone a radical change in shape. The near vertical bank has transformed into a steep and fairly uniform slope which is partially covered with some native vegetation. To the untrained eye, the channel bank along the study reach appears to be in its natural state.

The channel has tended to deepen along the study reach over the project life especially along the downstream portion. As the amount of scour along the revetment toe increases, the revetment rock slides down the underwater slope to protect the bank. The thickness of the upper portion of the revetment is reduced which increases the likelihood for additional erosion in this area.

VII. CONCLUSIONS

A. General. Conclusions reached relative to the performance of the windrow revetment placed at the Missouri River Vermillion Chute near Vermillion, South Dakota are as follows:

1. The process of obtaining a stable revetment armor for the flow regime which has prevailed in the Missouri River for the past several years has shown that the windrow revetment concept is a viable channel bank erosion protection alternative.

2. As the windrow revetment moved into place, the bank line along the study reach became more uniform; consequently, the Manning's roughness coefficient "n" is reduced.

3. The reduction in the rate of bank erosion was evaluated on the basis of annual prototype measurements. No significant lateral erosion was experienced at hydrographic ranges 4 and 6 between 1978 and 1979.

4. At this point in the life of the project, the initial objectives have been satisfied. The windrow revetment has prevented the loss of additional farm land and has kept the natural riverine environment disturbance at a minimum.

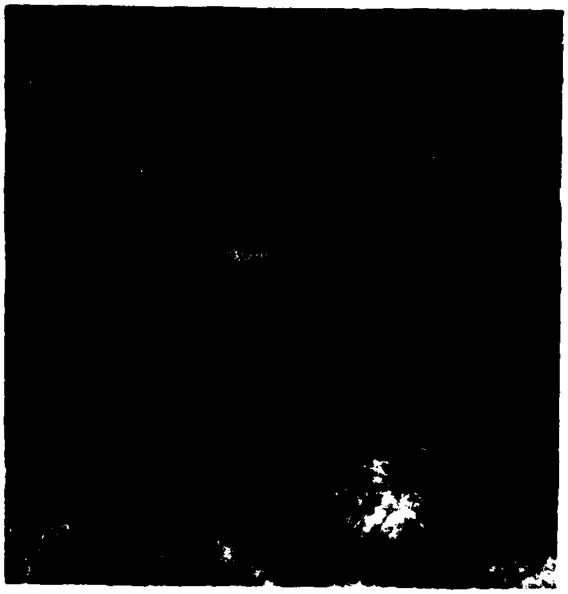
5. Economic considerations are important in selecting the type of bank erosion protection to be used on the Missouri River. The windrow revetment method of erosion control has proven to be economical, easily implemented and environmentally acceptable.

VIII. RECOMMENDATIONS

General. The ease of construction and the effectiveness in curtailing the rate of bank erosion has demonstrated the feasibility of the windrow revetment method for achieving river bank stabilization. The stone remaining in the windrow at this time should not be removed and used elsewhere because of the thinness of the upper portion of the revetment blanket and the possibilities of experiencing higher discharges in the study area. Higher discharges would raise the river stage enough to cause erosion in the thin upper portion of the windrow revetment. Without available windrow stone to feed down onto the revetment slope, the integrity of the windrow revetment would be in jeopardy. Therefore, project monitoring should continue in order to prevent a depletion of the windrow stone.

Photograph 13. Close-up view of the lower bank area showing windrow stone early in process of forming protective revetment. Date: 26 Oct 77

Photograph 14. Same as photograph 13 but at a different location. Date: 26 Oct 77



Photograph 15. Looking downstream at the beginning station of the windrow revetment (station 25+00) Date: 26 Oct 1977.

Photograph 16. Upstream view of windrow revetment. Date: 2 Dec 77

Photograph 17. Upstream view from approximately station 35+00. Date: 26 Oct 77

Photograph 18. Close-up view of stone which has dropped down from original placement in the windrow revetment. Date: 26 Oct 77

Photograph 19. View of flat overbank area upstream of the windrow revetment. Date: 29 May 1979

Photograph 20. Close-up view of windrow revetment. Date: 29 May 1979

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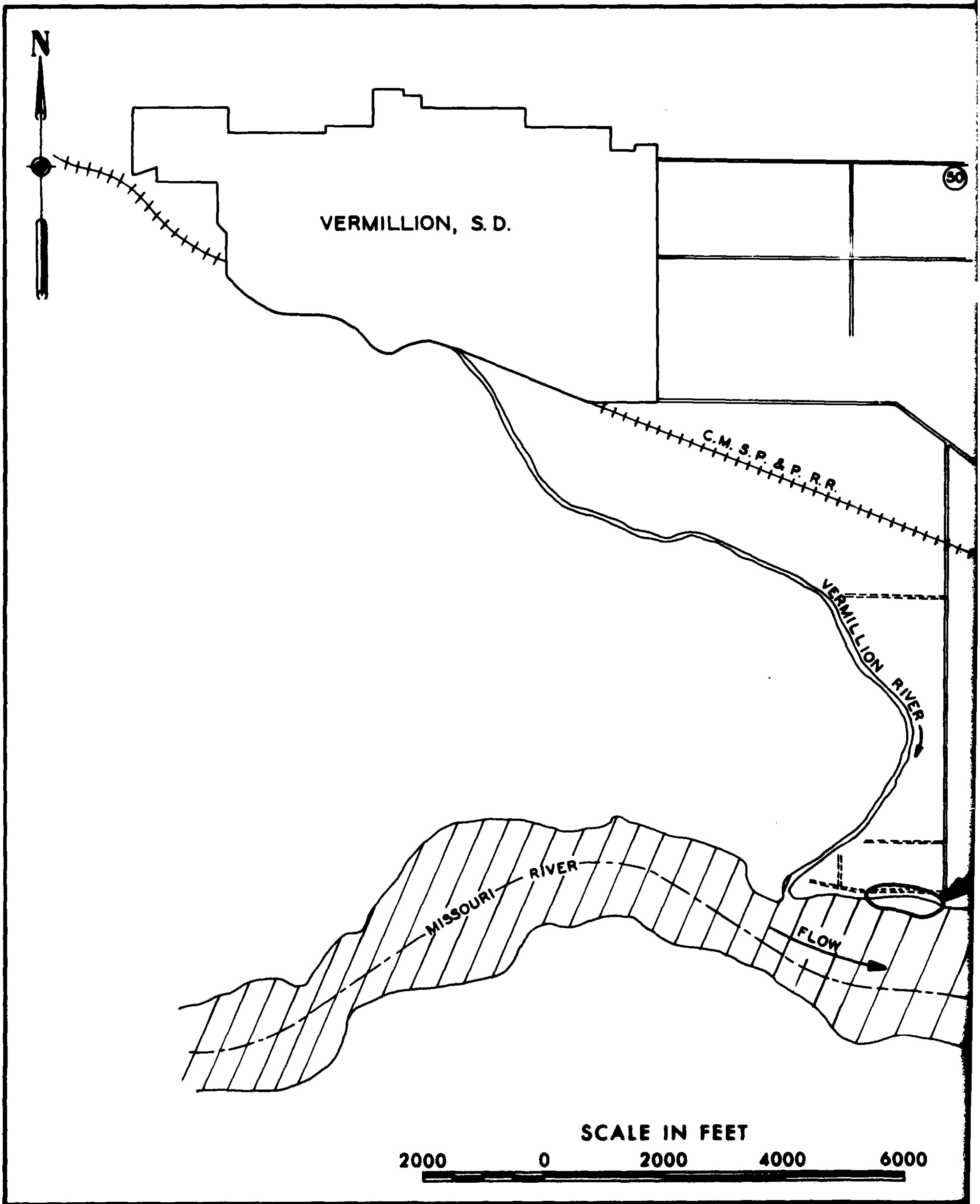
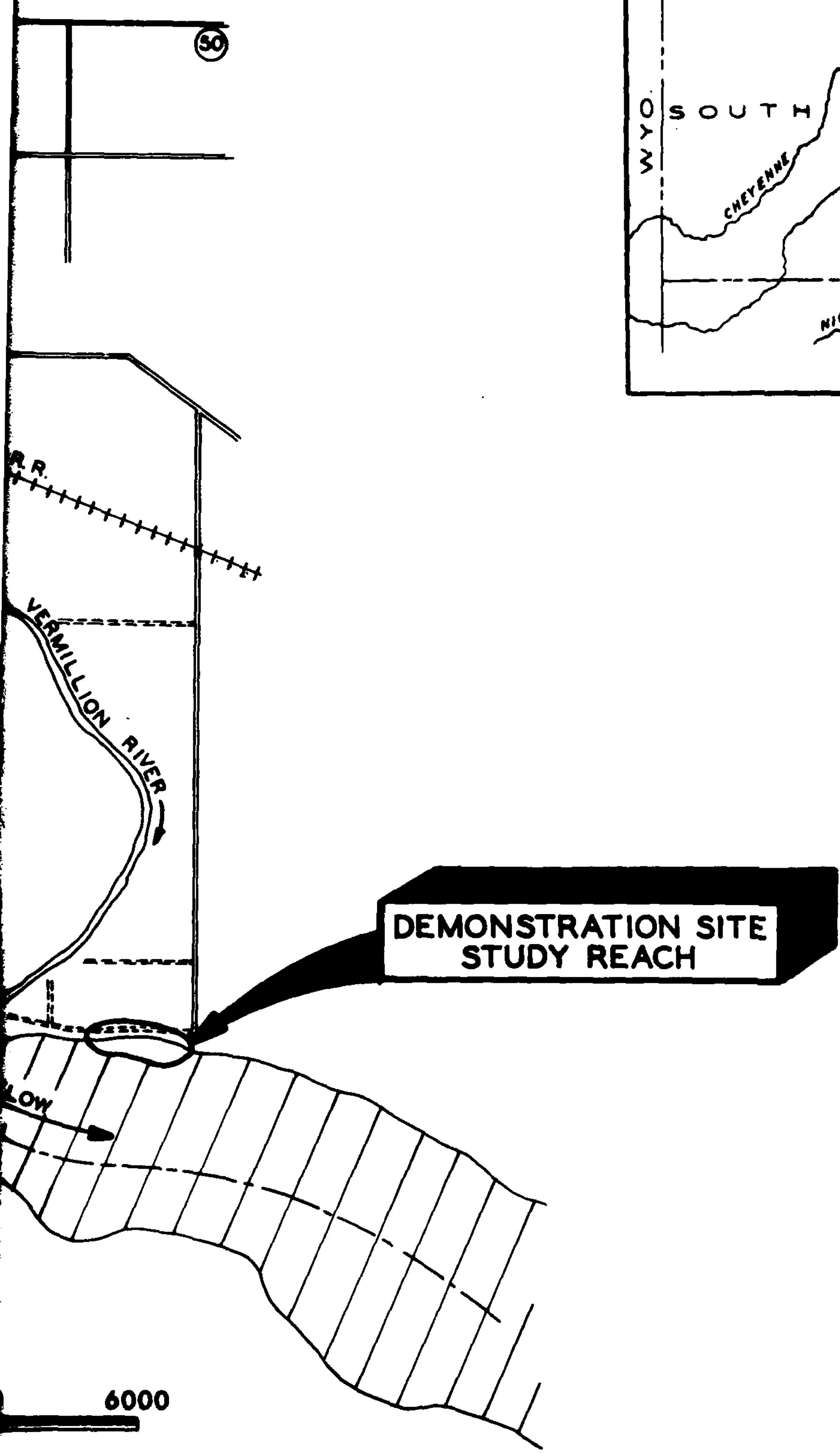
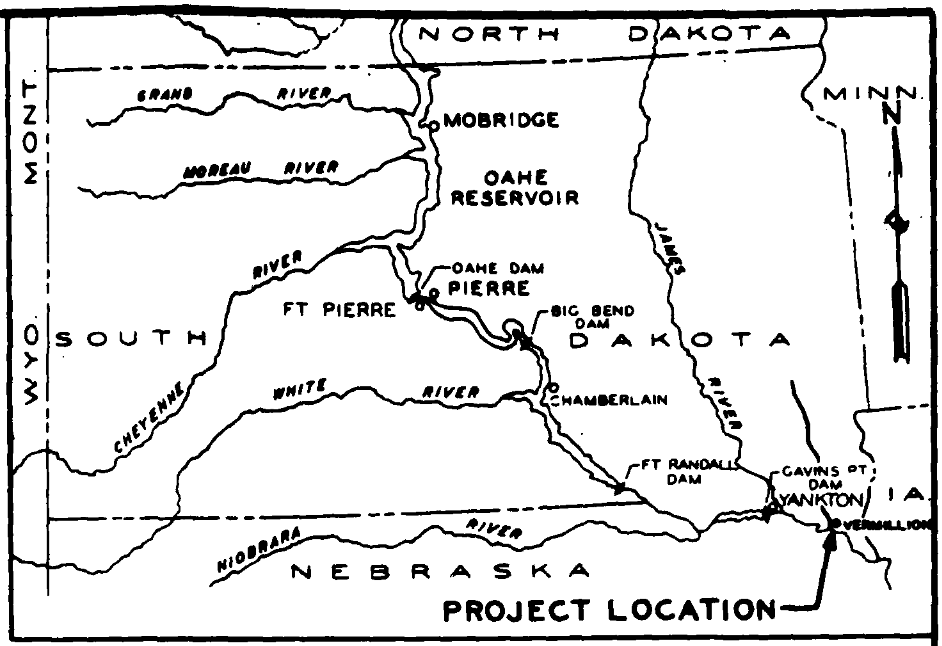
3. Task Committee on Channel Stabilization Works Committee on Regulation and Stabilization of Rivers, "Channel Stabilization or Alluvial Rivers Progress Report", Vol. 91, No. WW1, Feb 1965, pp 7-37.

4. U. S. Geological Survey, "Surface Water Supply of the United States 1959 - Part 6-A. Missouri River Basin Above Sioux City, Iowa", Geological Survey Water Supply Paper No. 1629 U. S. Government Printing Office, Washington, D. C., 1960, pp 359.


N
VERMILLION, S.D.
50
C.M. S.P. & P. R.R.
VERMILLION RIVER
MISSOURI RIVER
FLOW
SCALE IN FEET
2000 0 2000 4000 6000



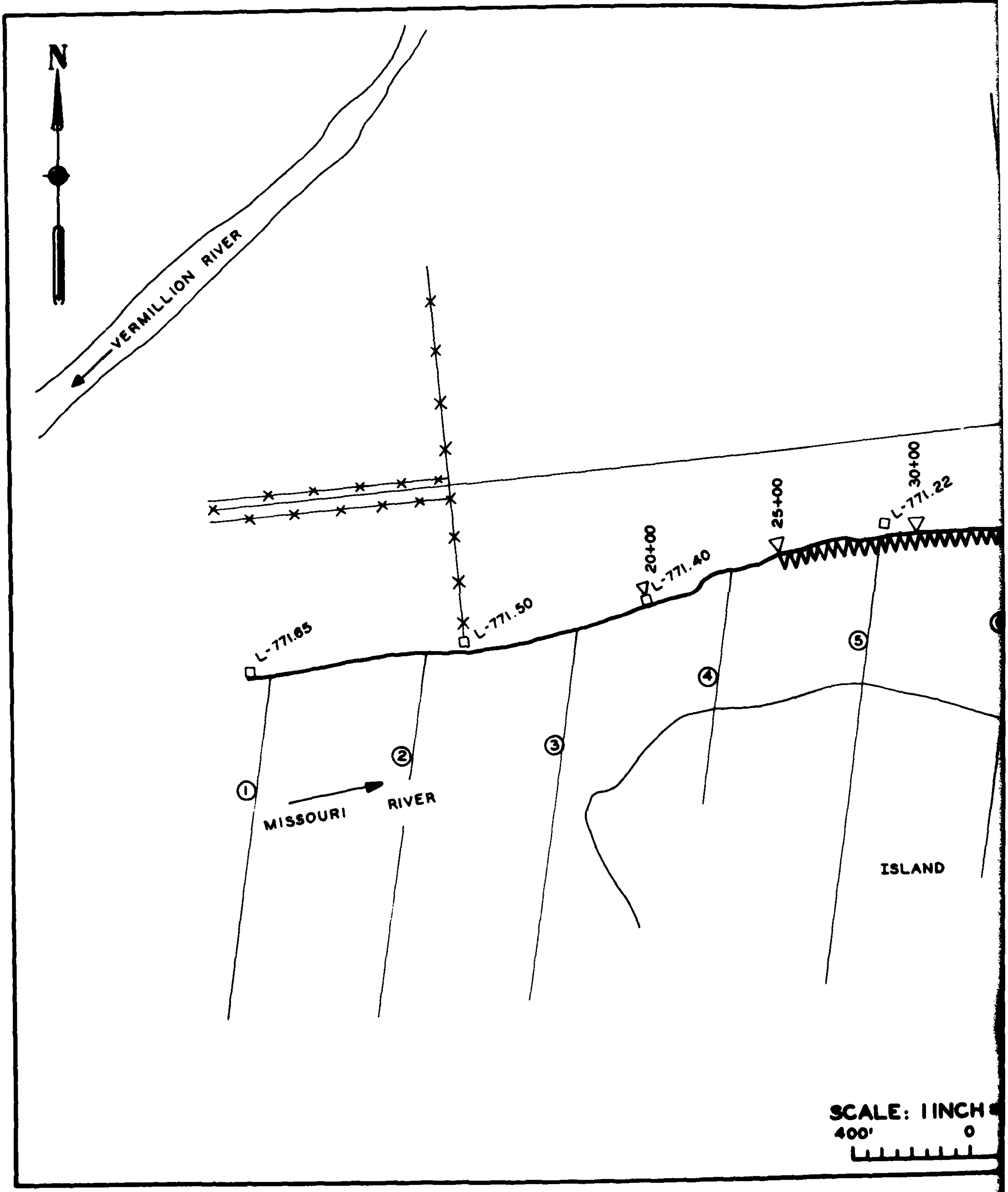


LOCATION MAP

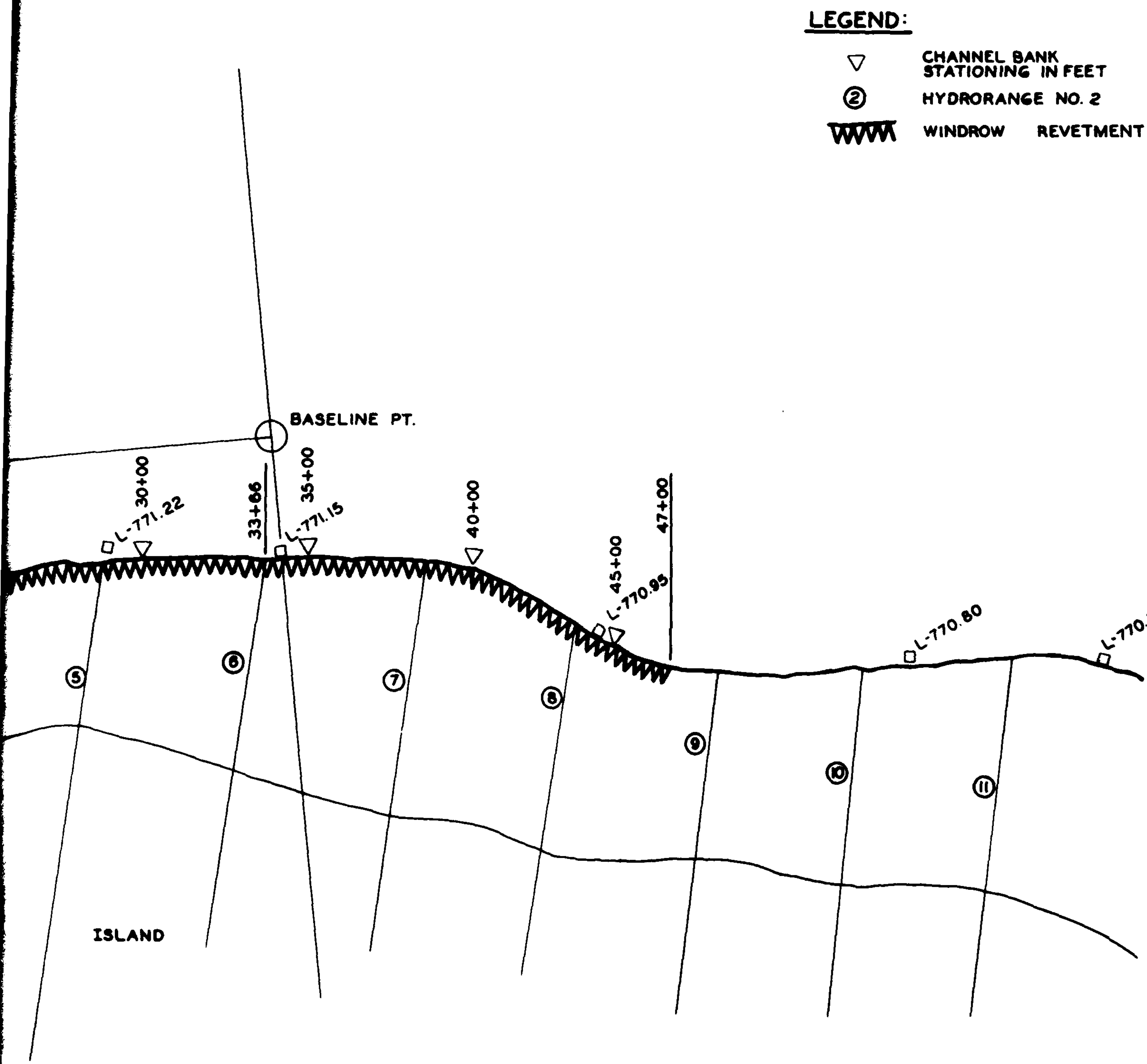
MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL
BANK PROTECTION
USING WINDROW REVETMENT
DEMONSTRATION SITE LOCATION MAPS
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN. 1980

7

PLATE I



N
VERMILLION RIVER
L-771.65
L-771.50
L-771.40
L-771.22
20+00
25+00
30+00
1
2
3
4
5
MISSOURI
RIVER
ISLAND
SCALE: 1 INCH
400'
0

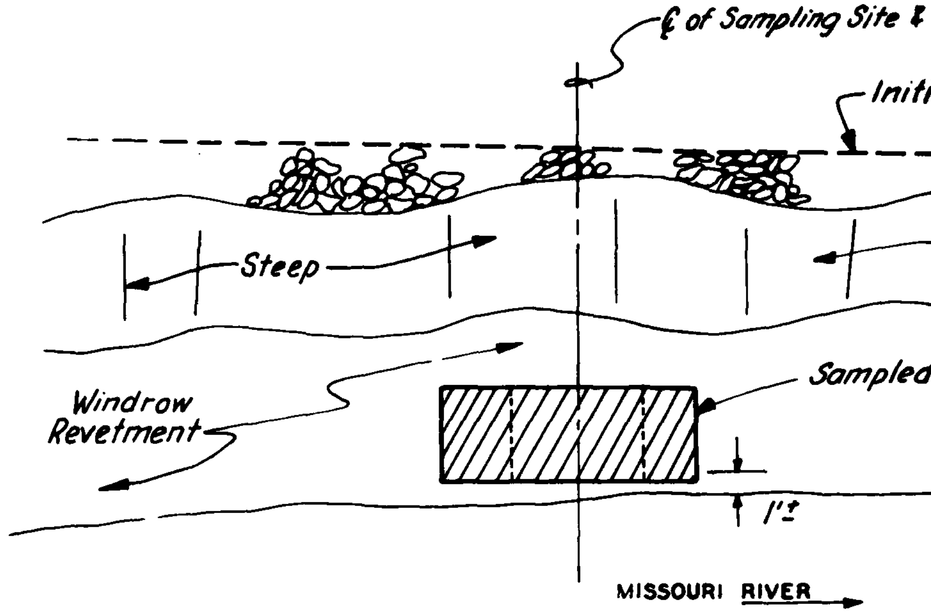


MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL
BANK PROTECTION
USING WINDROW REVETMENT
REVETMENT LAYOUT
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN 1980

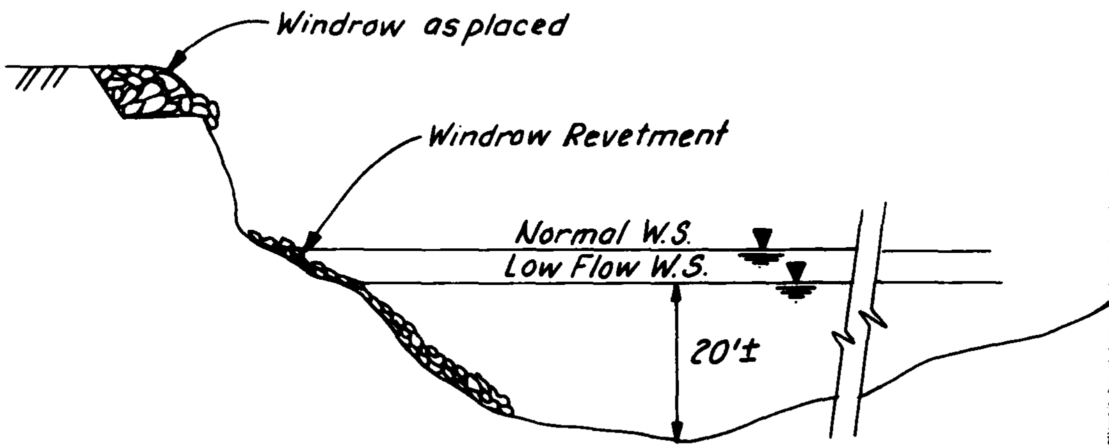
SCALE: 1 INCH = 400 FEET
400' 0 400'

2

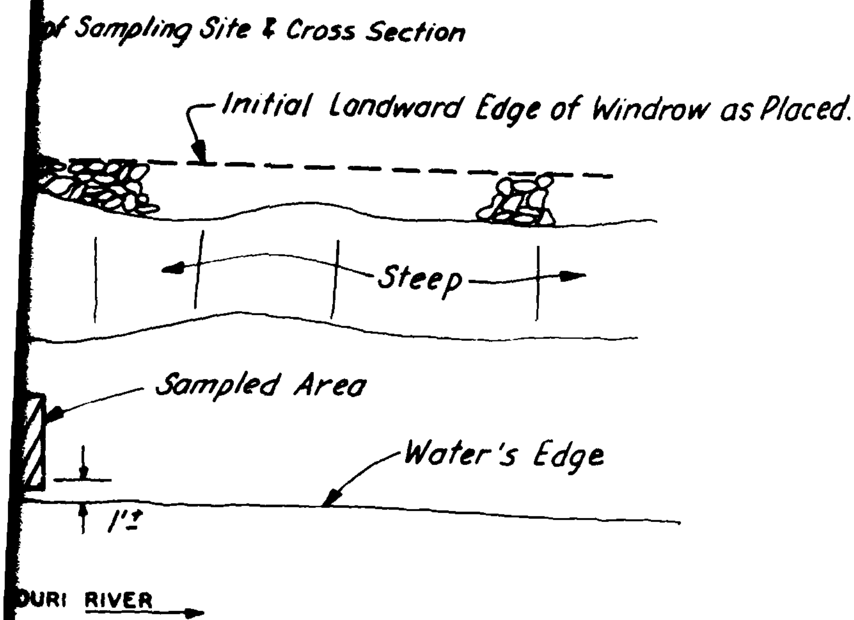
PLATE 2



PLAN
NO SCALE



APPROXIMATE ℄ CROSS SECTION
NO SCALE



PLAN
NO SCALE

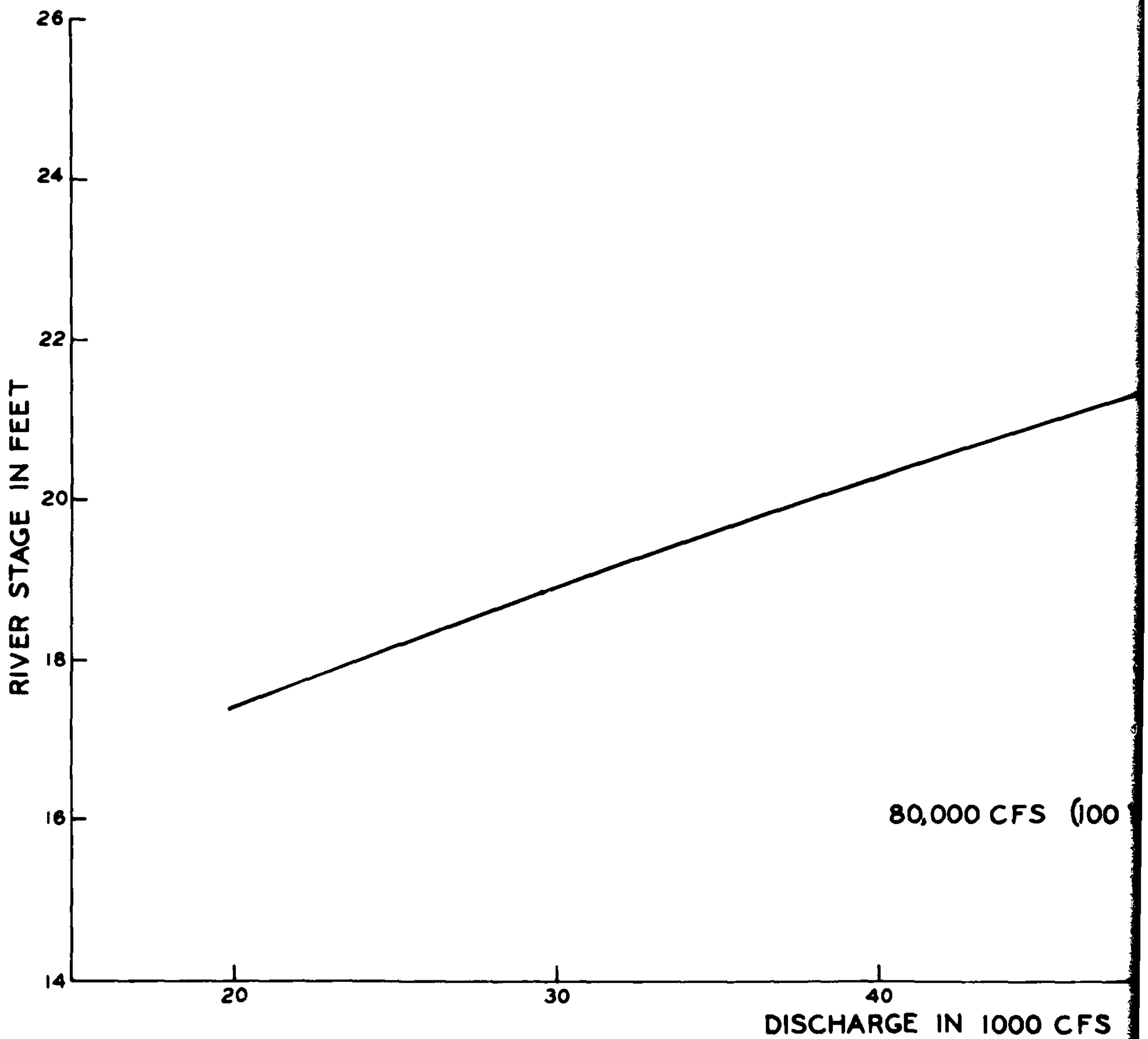
OSS SECTION

MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL
BANK PROTECTION
USING WINDROW REVETMENT

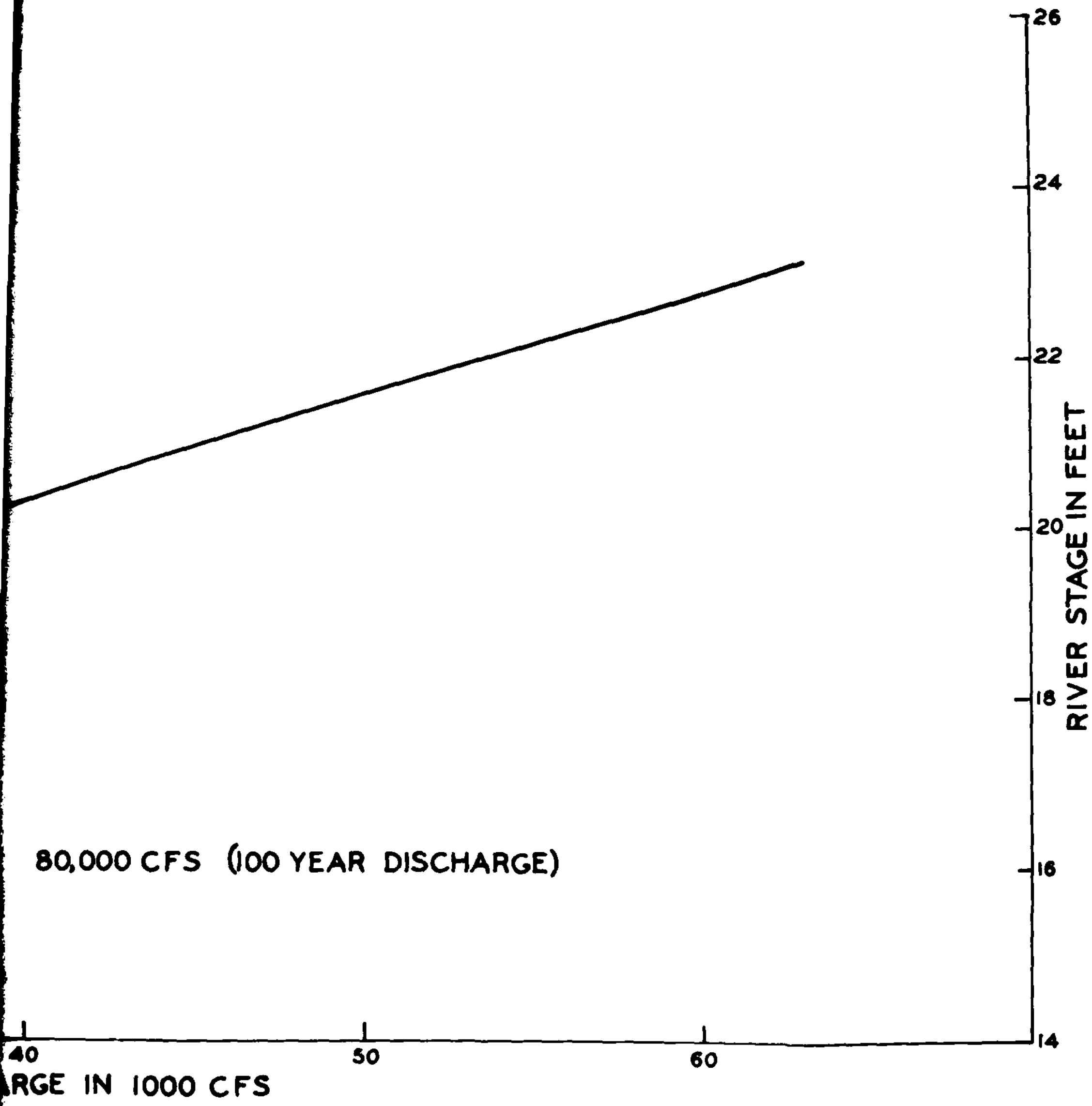
TYPICAL PLAN AND
SECTION OF SAMPLING SITE

U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
JAN 1980

PLATE 3



RIVER STAGE IN FEET
26
24
22
20
18
16
14
80,000 CFS (100
20
30
40
DISCHARGE IN 1000 CFS



MISSOURI RIVER

SECTION 32 STREAMBANK EROSION CONTROL

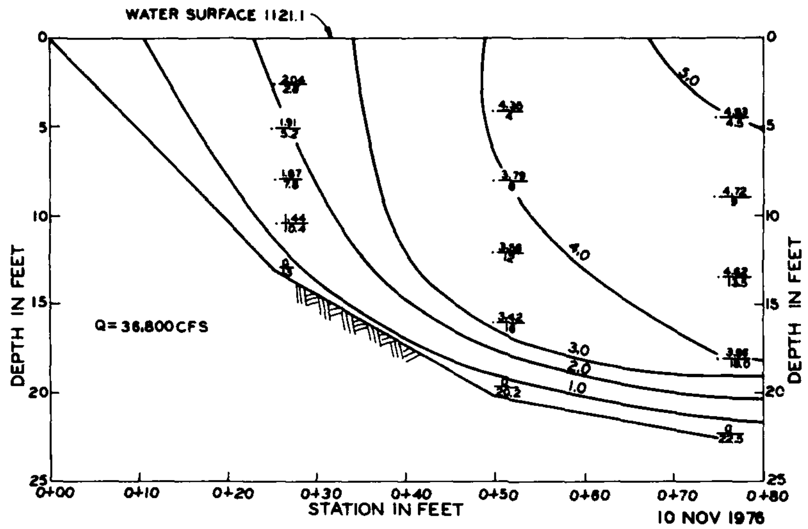
BANK PROTECTION
USING WINDROW REVETMENT

STUDY AREA DISCHARGE RATING CURVE

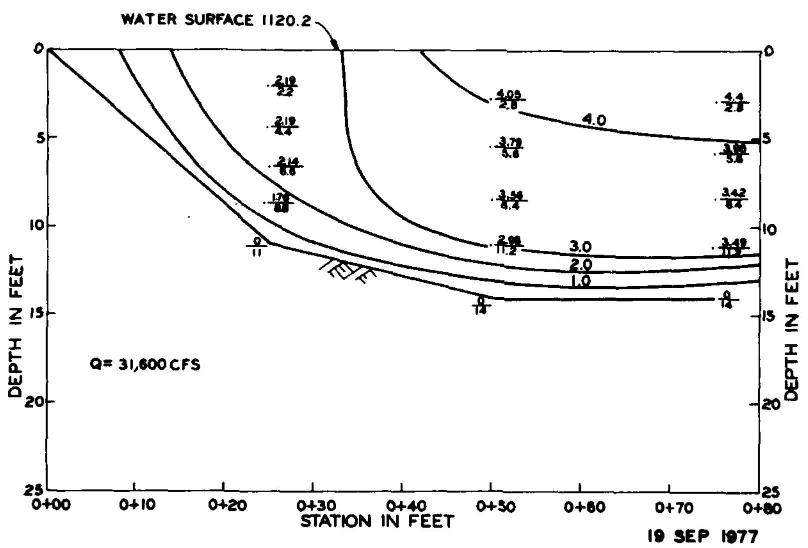
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN 1980

2

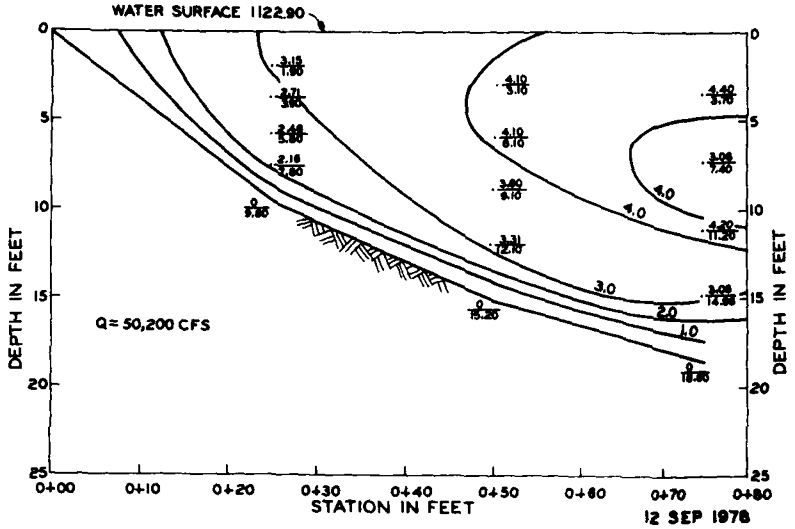
PLATE 4

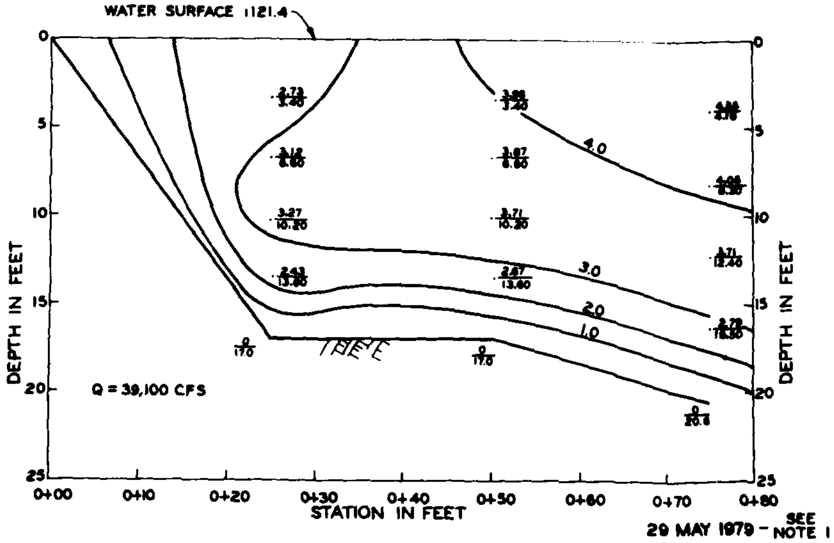


WATER SURFACE 1121.1
DEPTH IN FEET
Q= 36,800 CFS
STATION IN FEET
10 NOV 1976



WATER SURFACE 1120.2
DEPTH IN FEET
Q= 31,600 CFS
STATION IN FEET
19 SEP 1977





NOTES:

1. THE 29 MAY 1979 SURVEY WAS TAKEN 280 FEET DOWNSTREAM FROM HYDROGRAPH RANGE #4.
2. RATIO VALUES ARE VELOCITY (FPS) OVER DEPTH (FT).

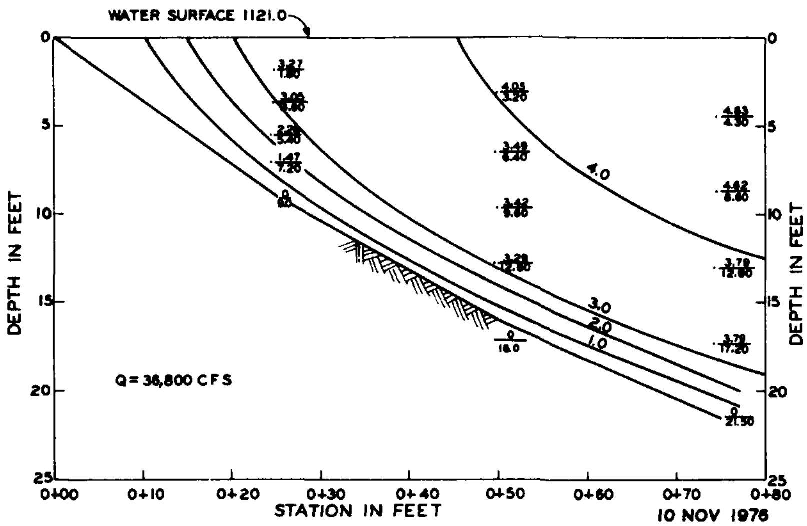
MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL

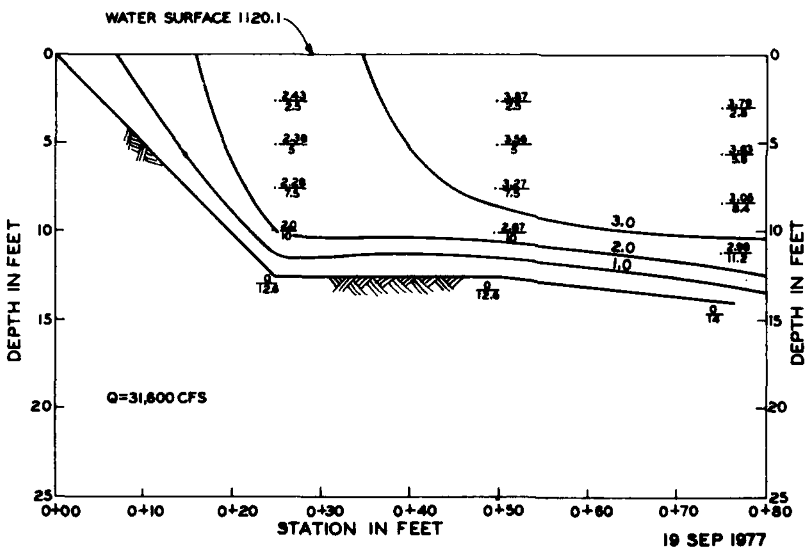
BANK PROTECTION USING WINDROW REVETMENT

HYDROGRAPH RANGE #4 ISOVELS

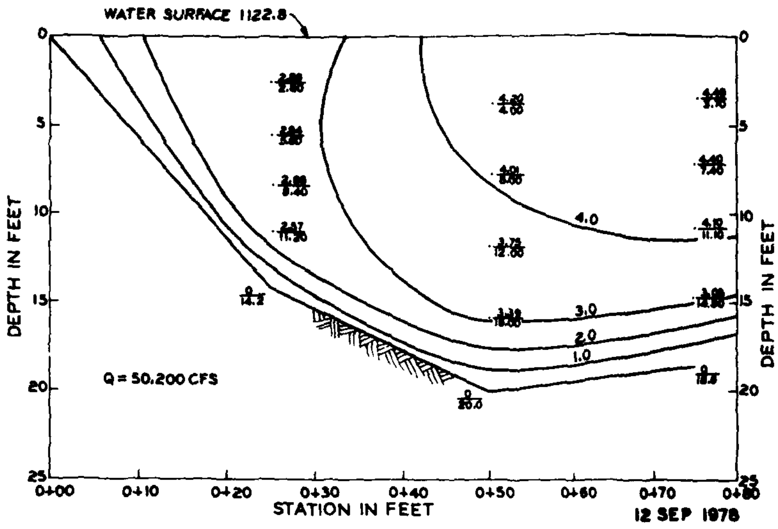
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
JAN. 1980

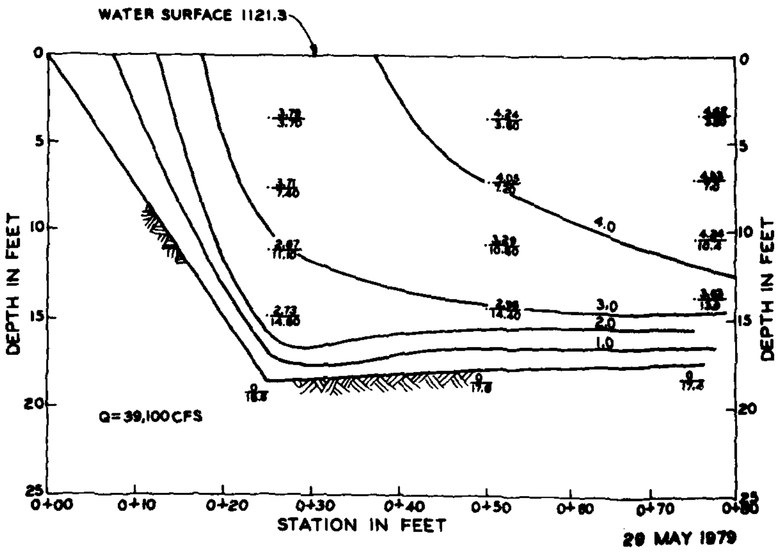
PLATE


WATER SURFACE 1121.0
DEPTH IN FEET
STATION IN FEET
Q= 38,800 CFS
4.0
3.0
2.0
1.0
10 NOV 1976


WATER SURFACE 1120.1
DEPTH IN FEET
STATION IN FEET
Q=31,800 CFS
3.0
2.0
1.0
19 SEP 1977

DEPTH IN FEET
DEPTH IN FEET



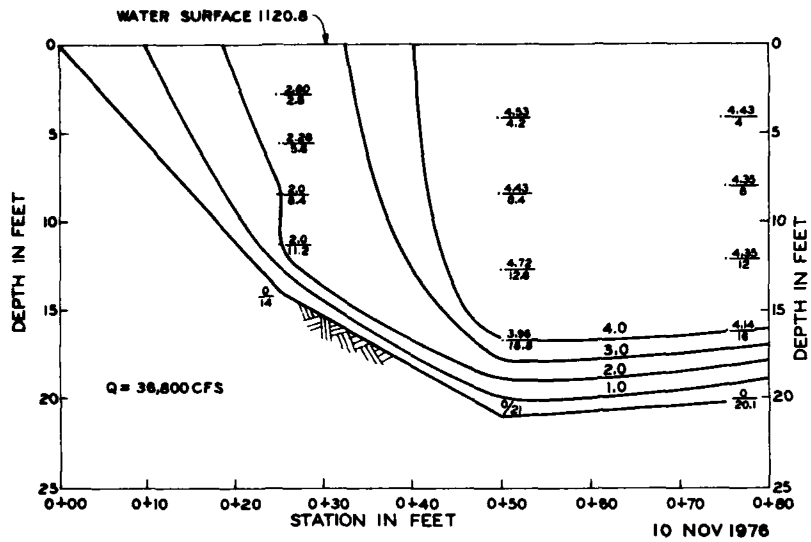


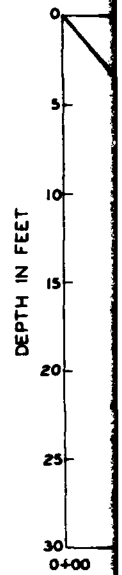
NOTE:

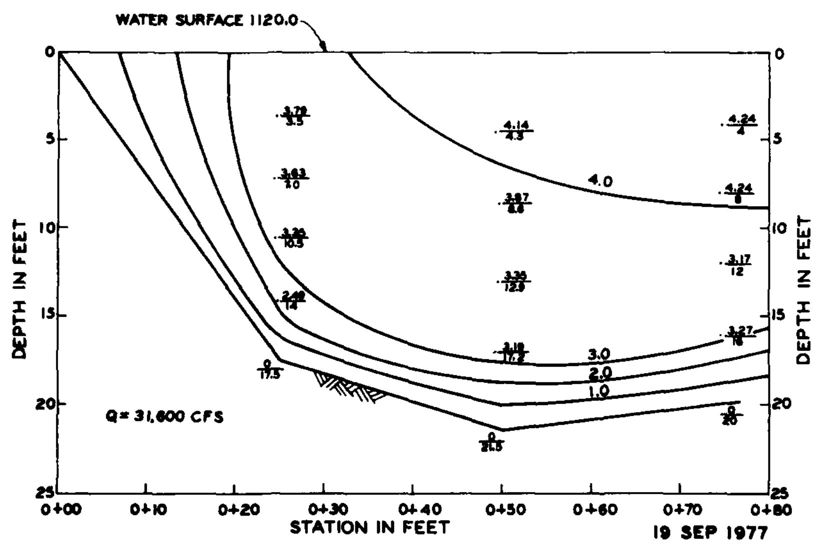
1. RATIO VALUES ARE VELOCITY (FPS) OVER DEPTH (FT).

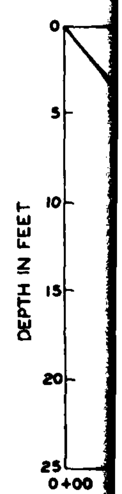
MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL
BANK PROTECTION USING WINDROW REVETMENT
HYDROGRAPH RANGE #5 ISOVELS
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
JAN. 1980

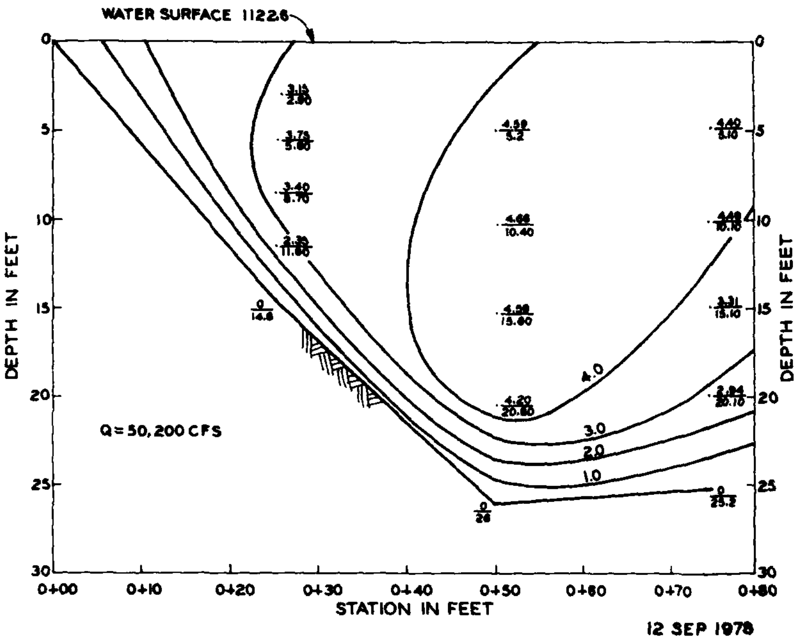
PLATE 6

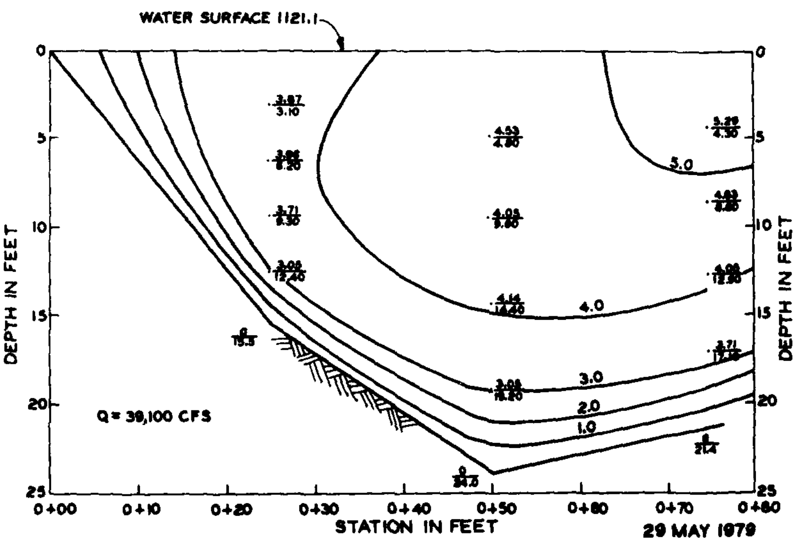

WATER SURFACE 1120.8
DEPTH IN FEET
STATION IN FEET
Q= 38,800 CFS
4.0
3.0
2.0
1.0
0+00
0+10
0+20
0+30
0+40
0+50
0+60
0+70
0+80
10 NOV 1976


DEPTH IN FEET
0+00


WATER SURFACE 1120.0
DEPTH IN FEET
STATION IN FEET
Q= 31,600 CFS
4.0
3.0
2.0
1.0
0+00
0+10
0+20
0+30
0+40
0+50
0+60
0+70
0+80
19 SEP 1977


DEPTH IN FEET
0+00





NOTE:

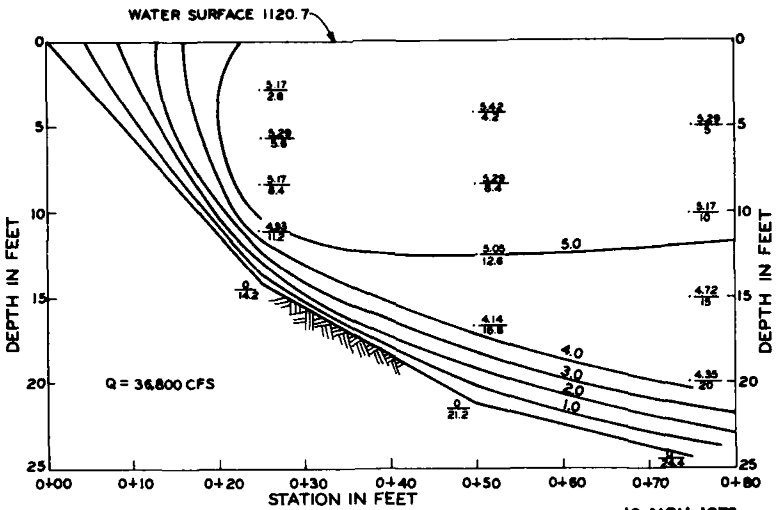
1. RATIO VALUES ARE VELOCITY (FPS) OVER DEPTH (FT).

MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL

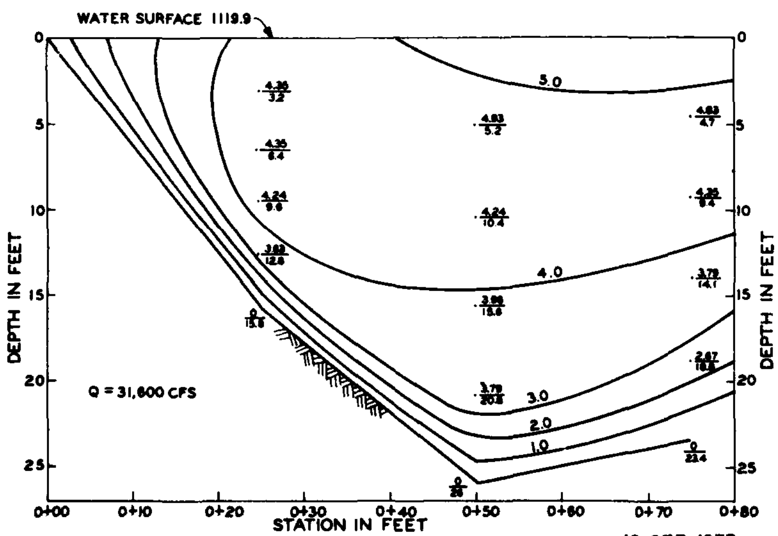
BANK PROTECTION USING WINDROW REVETMENT

HYDROGRAPH RANGE #7 ISOVELS

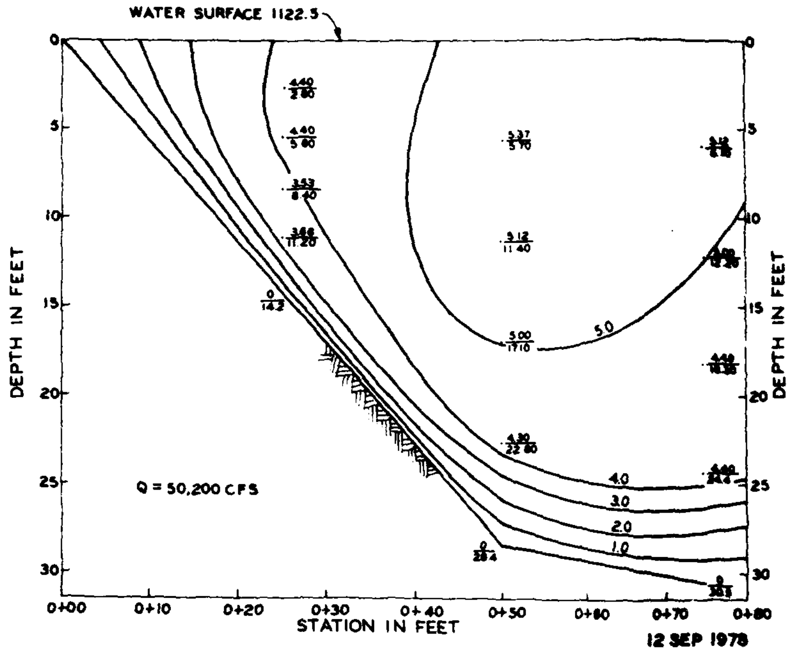
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN. 1980

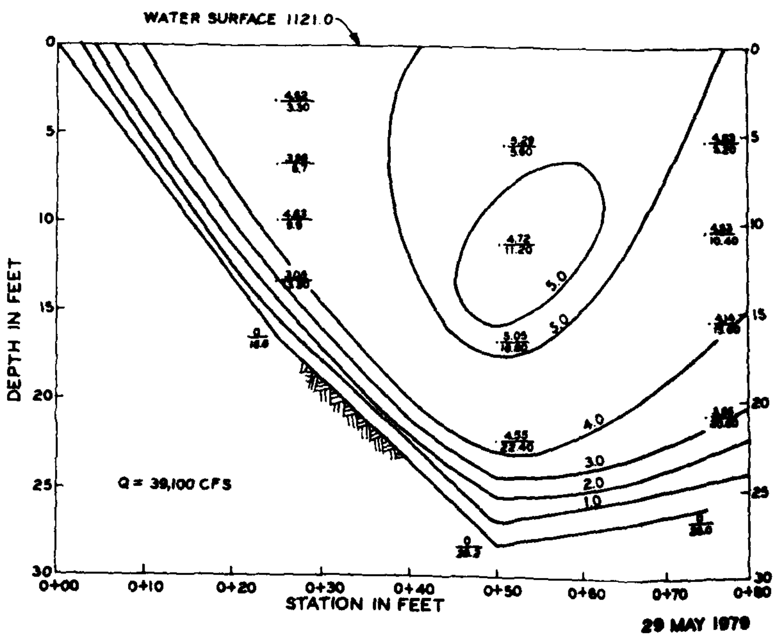


10 NOV 1976



19 SEP 1977





NOTE:

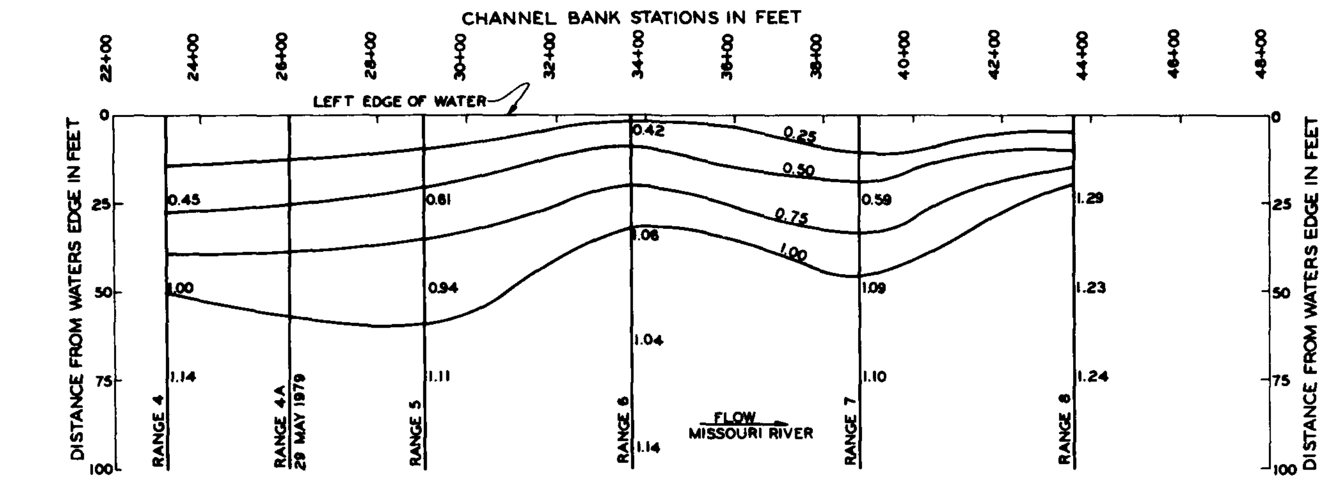
1. RATIO VALUES ARE VELOCITY (FPS) OVER DEPTH (FT).

MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL

BANK PROTECTION USING WINDROW REVETMENT

HYDROGRAPH RANGE #8 ISOVELS

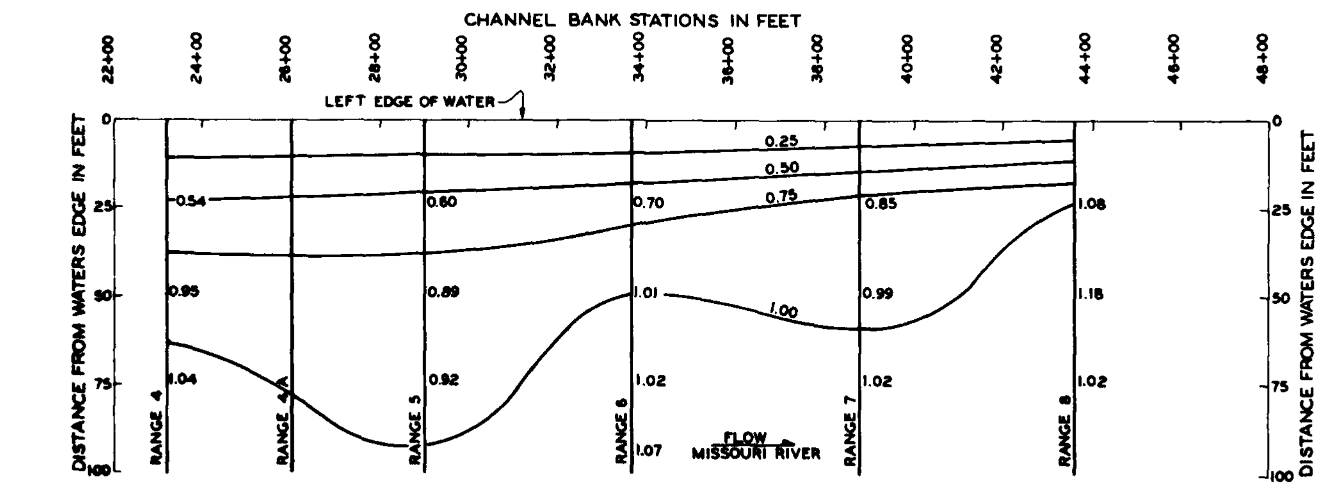
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN. 1980



RANGE #6 AVG. VEL. FOR CHANNEL = 3.90 FPS

10 NOV. 1976
% Q' = 85% - SEE NOTE 1
Q_{GP} = 35,000 CFS
Q_{YG} = 36,800 CFS
Q_{LCV} = 31,228 CFS
SEE NOTE 4

RAN



RANGE #6 AVG. VEL. FOR CHANNEL = 3.89 FPS

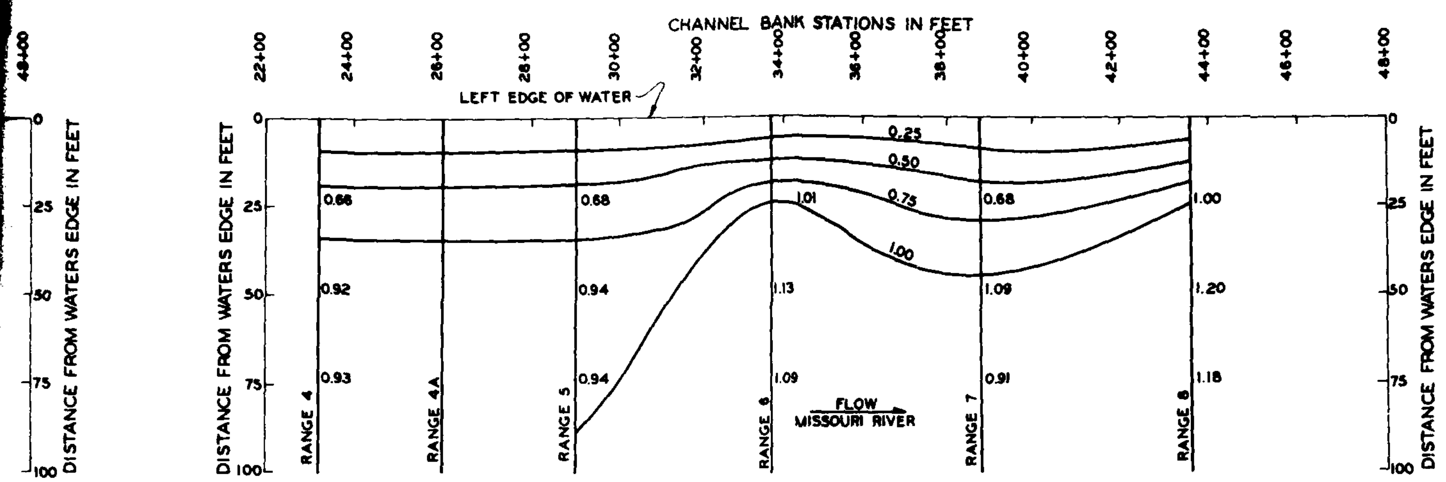
19 SEP 1977
%Q' = 89%
Q_{GP} = 31,700 CFS
Q_{YG} = 31,800 CFS
Q_{LCV} = 28,180 CFS

RANG

NOTES:
1. %Q'
IN TH
TOTA

2. VALU
THE
THE
THE
OCIT

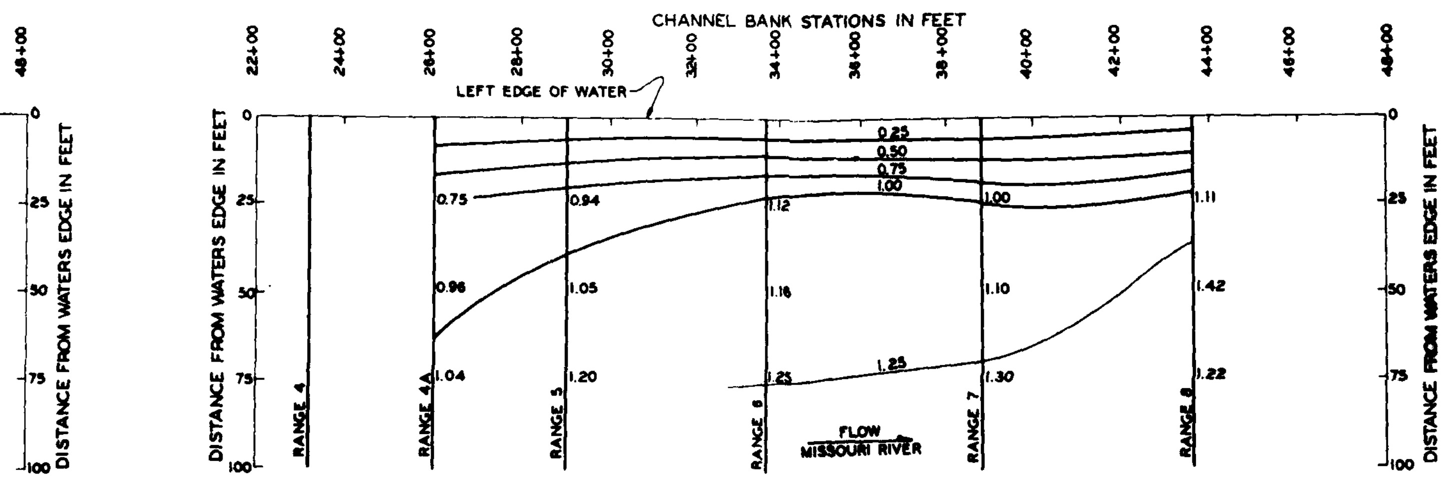
3. THE
ALON
PUTE
AT G



RANGE #6 AVG. VEL. FOR CHANNEL = 4.03 FPS

1976
%- SEE NOTE 1
000 CFS
000 CFS } SEE NOTE 4
228 CFS

12 SEP 1978
%Q' = 74%
Q_{GP} = 50,000 CFS
Q_{YG} = 50,200 CFS
Q_{LCV} = 37,150 CFS



RANGE #6 AVG. VEL. FOR CHANNEL = 3.45 FPS

1977
%
00 CFS
00 CFS
00 CFS

29 MAY 1979
%Q' = 72%
Q_{GP} = 38,000 CFS
Q_{YG} = 38,100 CFS
Q_{LCV} = 28,105 CFS

NOTES:

1. %Q' IS PERCENT OF THE DISCHARGE IN THE LEFT CHANNEL Q_{LCV}, TO THE TOTAL DISCHARGE, Q_{YG}.
2. VALUES ALONG THE RANGE LINES ARE THE RATIOS OF AVERAGE VELOCITY IN THE VERTICAL AT THAT POINT TO THE AVERAGE LEFT CHANNEL VELOCITY AT RANGE 6.
3. THE AVERAGE VELOCITY AT EACH POINT ALONG THE RANGE LINES WAS COMPUTED FROM THE VELOCITIES MEASURED AT 0.2 AND 0.8 OF THE DEPTH.
4. Q_{GP} = DISCHARGE AT GAVINS POINT RESERVOIR.
Q_{YG} = DISCHARGE AT YANKTON, S.D. GAGE.
Q_{LCV} = DISCHARGE IN LEFT CHANNEL OF THE TEST REACH D/S FROM VERMILLION RIVER.
5. THE 10 NOV. 1976 VELOCITY SURVEY WAS TAKEN PRIOR TO CONSTRUCTION OF THE WINDROW.

MISSOURI RIVER

SECTION 32 STREAMBANK EROSION CONTROL

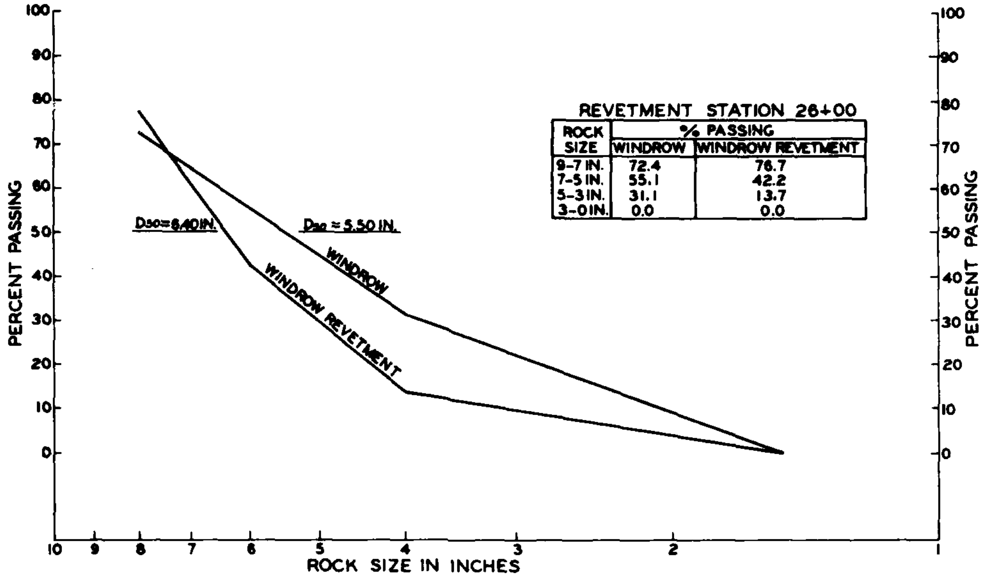
BANK PROTECTION USING WINDROW REVETMENT

DEMONSTRATION SITE VELOCITY TRENDS (NONDIMENSIONALIZED)

U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA

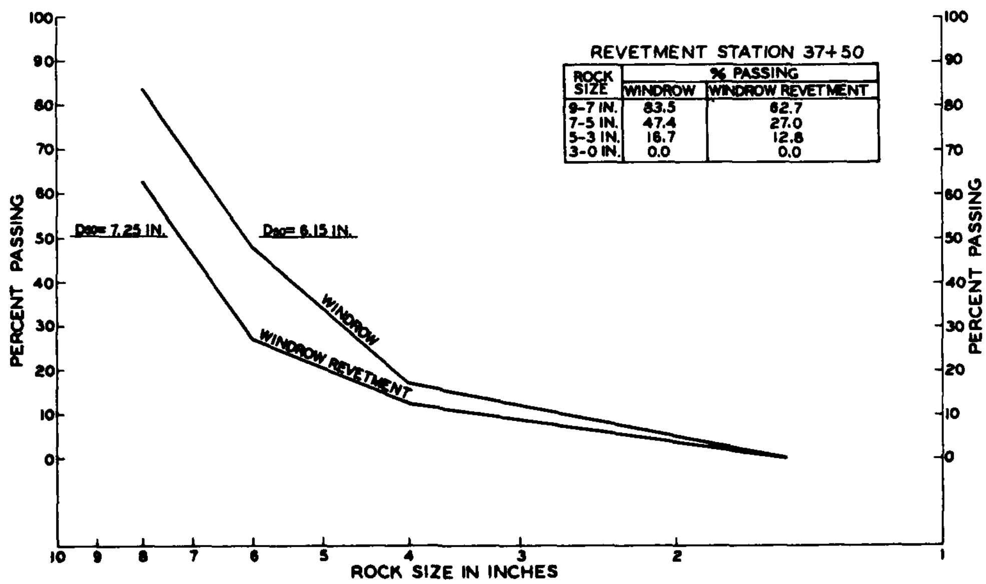
JAN. 1980

PLATE



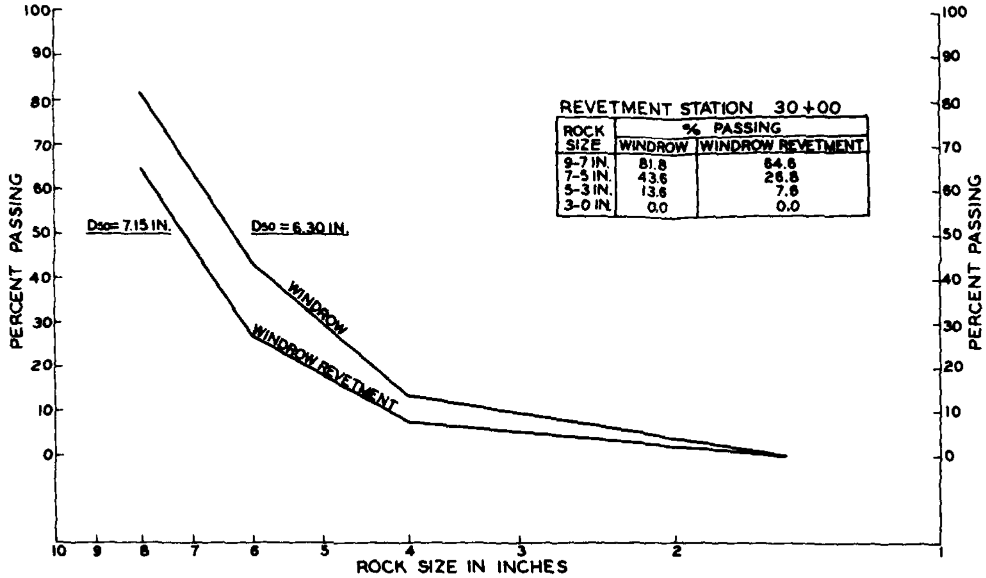
REVETMENT STATION 26+00

ROCK SIZE	% PASSING WINDROW	% PASSING WINDROW REVETMENT
9-7 IN.	72.4	76.7
7-5 IN.	55.1	42.2
5-3 IN.	31.1	13.7
3-0 IN.	0.0	0.0



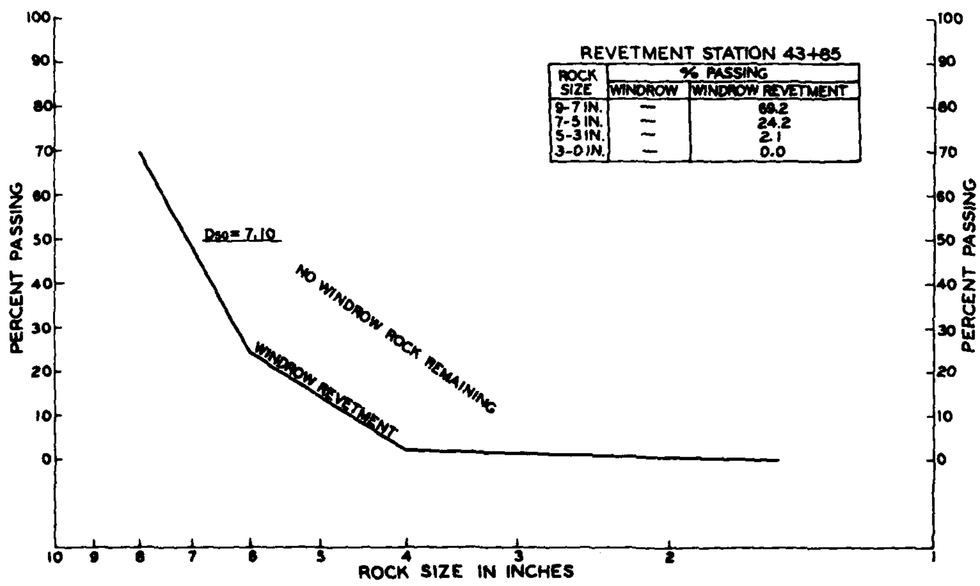
REVETMENT STATION 37+50

ROCK SIZE	% PASSING WINDROW	% PASSING WINDROW REVETMENT
9-7 IN.	83.5	62.7
7-5 IN.	47.4	27.0
5-3 IN.	16.7	12.8
3-0 IN.	0.0	0.0



REVETMENT STATION 30+00

ROCK SIZE	% PASSING	
	WINDROW	WINDROW REVETMENT
9-7 IN.	81.8	64.6
7-5 IN.	43.6	26.8
5-3 IN.	13.6	7.8
3-0 IN.	0.0	0.0



REVETMENT STATION 43+85

ROCK SIZE	% PASSING	
	WINDROW	WINDROW REVETMENT
9-7 IN.	—	69.2
7-5 IN.	—	24.2
5-3 IN.	—	2.1
3-0 IN.	—	0.0

NOTES:

1. FIELD DATA WAS ACQUIRED ON 2 DEC. 1977.
2. GRAPHS DO NOT INCLUDE THE +9 IN. MATERIAL OR THE FINE MATERIAL.

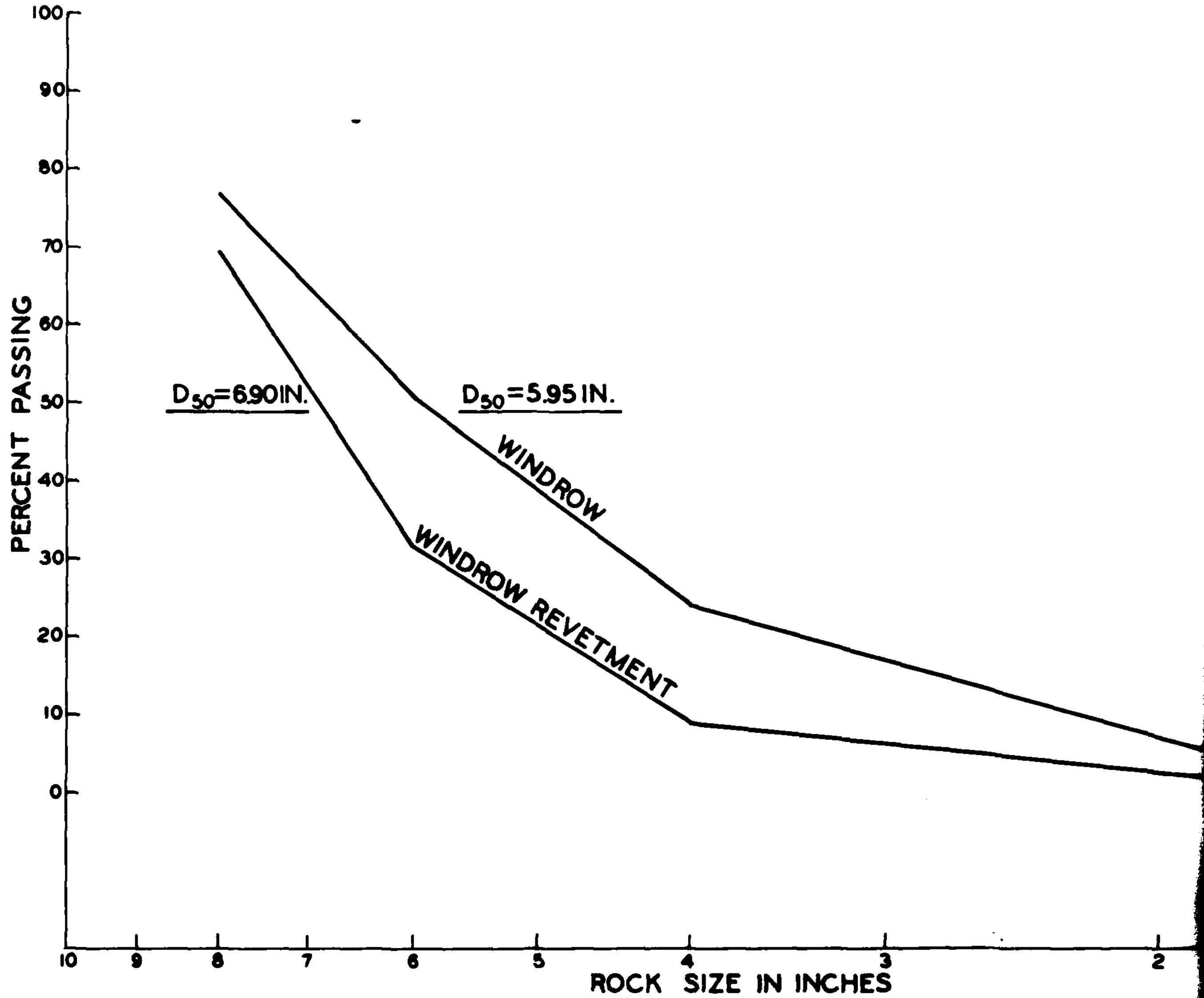
MISSOURI RIVER

SECTION 32 STREAMBANK EROSION CONTROL

BANK PROTECTION USING WINDROW REVETMENT

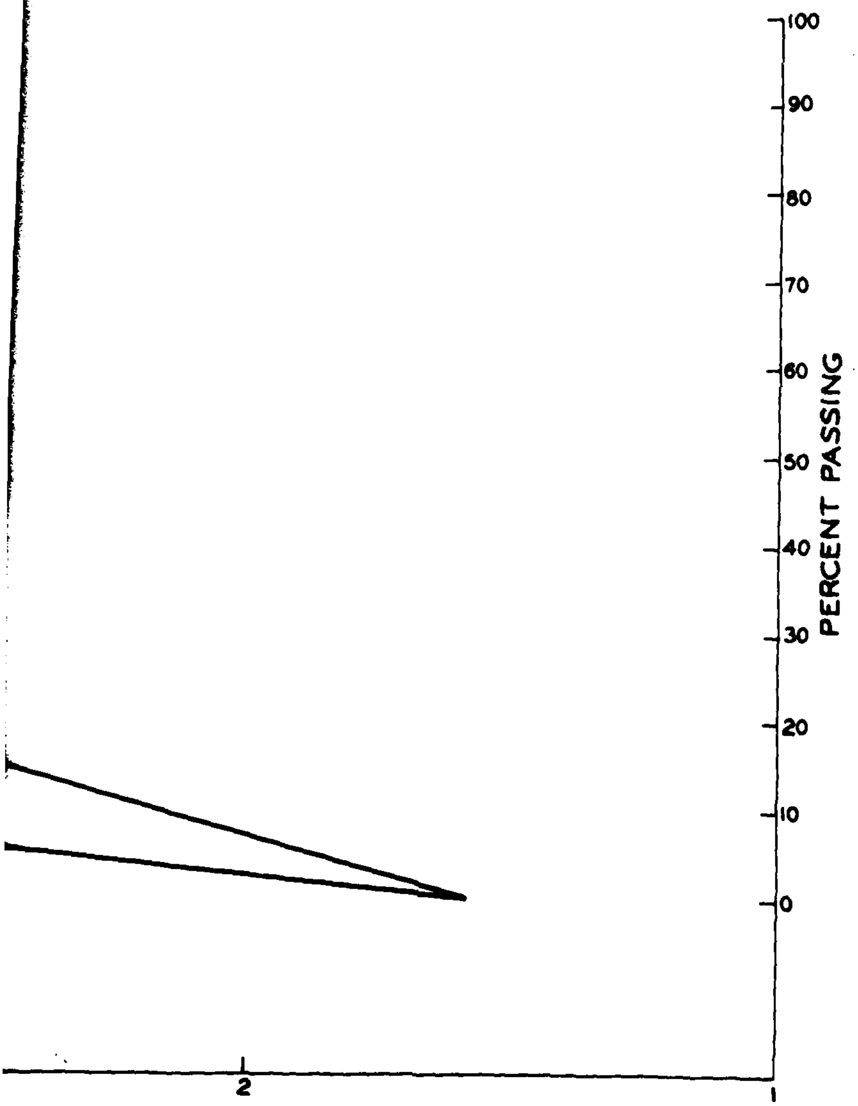
ROCK SIZE DISTRIBUTION BY STATIONS

U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
JAN. 1980


100
90
80
70
60
50
40
30
20
10
0
PERCENT PASSING
D50=6.90 IN.
D50=5.95 IN.
WINDROW
WINDROW REVETMENT
10
9
8
7
6
5
4
3
2
ROCK SIZE IN INCHES

ROCK DISTRIBUTION

ROCK SIZE	% PASSING	
	WINDROW	WINDROW REVETMENT
9-7 IN.	76.7	69.3
7-5 IN.	50.8	31.3
5-3 IN.	24.1	9.0
3-0 IN.	0.0	0.0



NOTES:

1. DISTRIBUTION VALUES EXCLUDE THE +9" MATERIAL AND THE FINE MATERIAL.
2. FIELD ROCK SIZE MEASUREMENTS WERE CONDUCTED 2 DEC. 1977.

MISSOURI RIVER

SECTION 32 STREAMBANK EROSION CONTROL

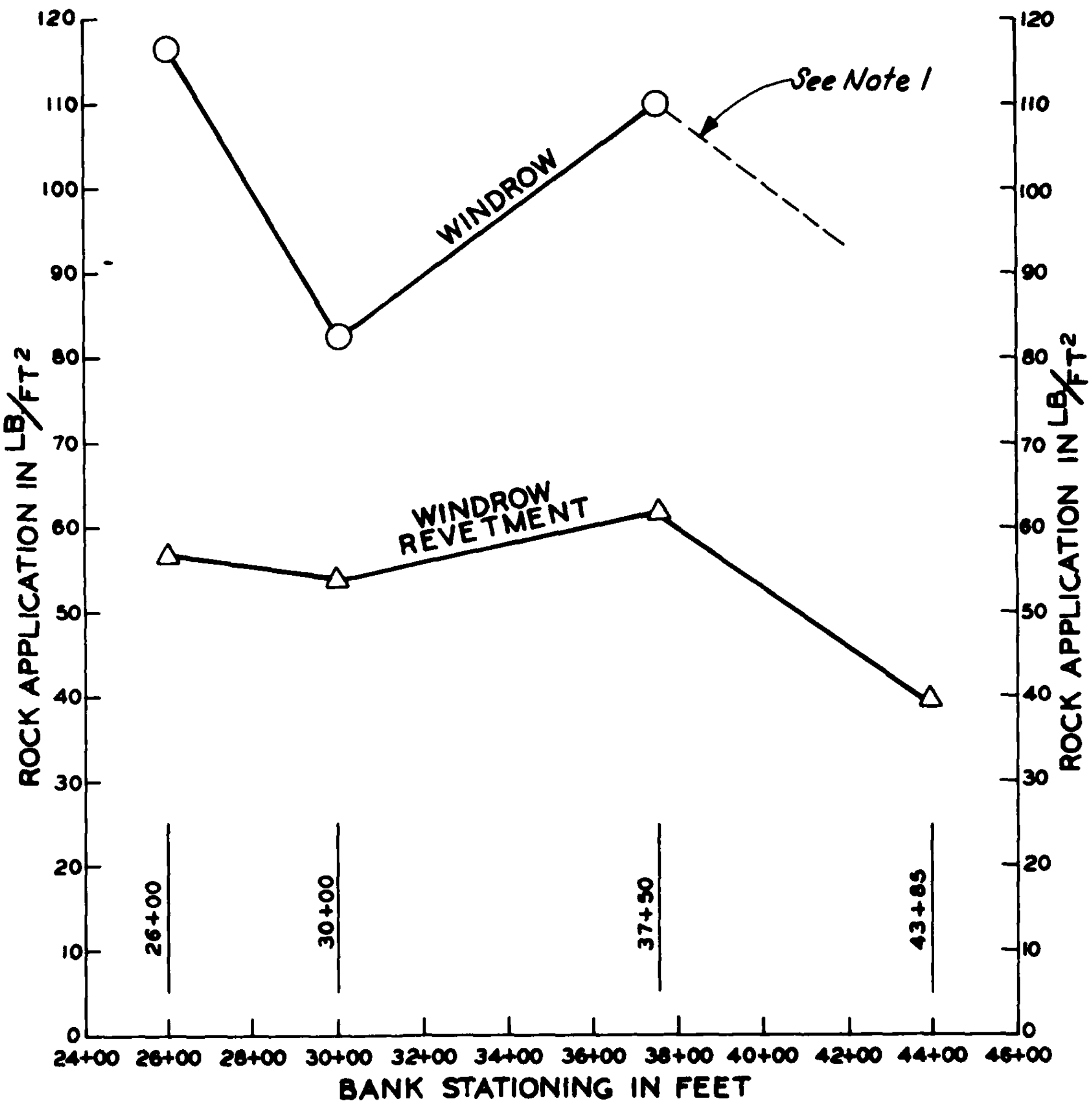
BANK PROTECTION USING WINDROW REVETMENT

COMPOSITE ROCK SIZE DISTRIBUTION CURVE

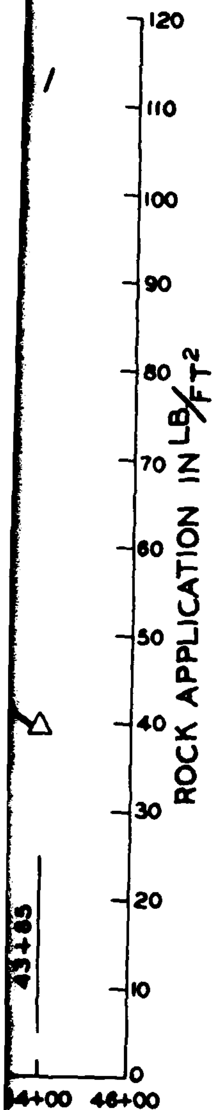
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN 1980

V

PLATE 1



ROCK APPLICATION IN LB/FT²
WINDROW
See Note 1
WINDROW REVETMENT
26+00
30+00
37+50
43+85
24+00 26+00 28+00 30+00 32+00 34+00 36+00 38+00 40+00 42+00 44+00 46+00
BANK STATIONING IN FEET

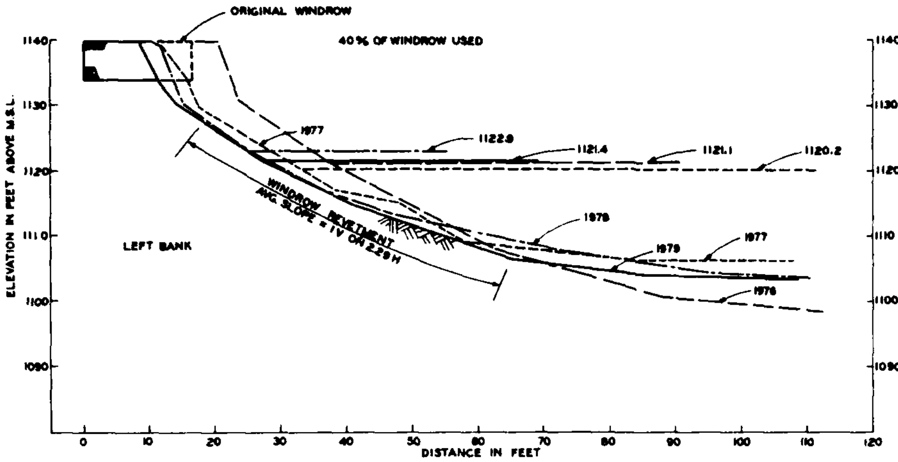


NOTES:

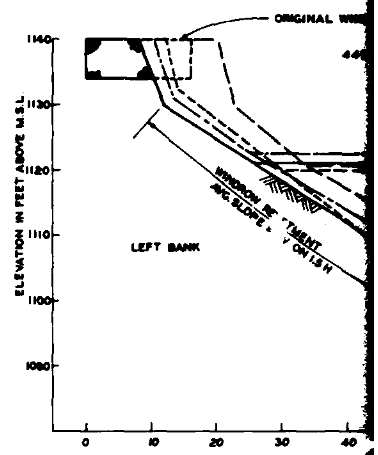
1. AT BANK STATION 43+85 ALL FIELD-STONE MATERIAL IN THE WINDROW HAS BEEN USED ON THE WINDROW REVETMENT.
2. FIELD MEASUREMENTS WERE TAKEN 2 DEC. 1977.

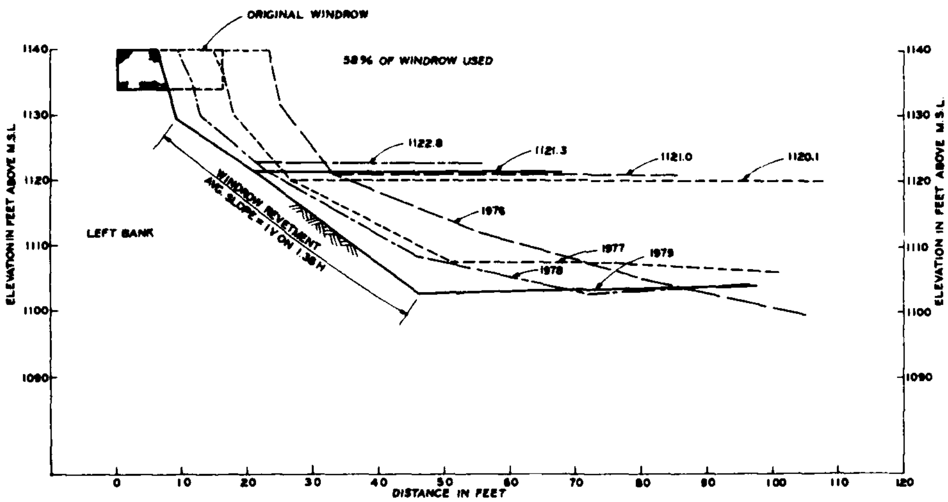
MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL
BANK PROTECTION
USING WINDROW REVETMENT
ROCK APPLICATION GRAPH
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN. 1980

PLATE 1

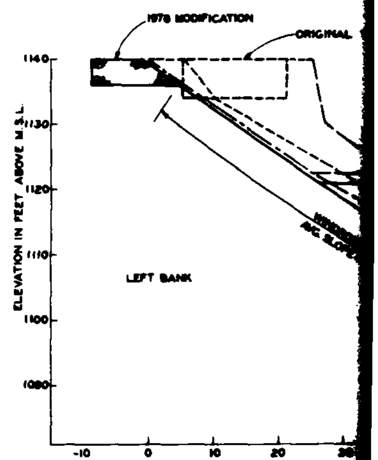


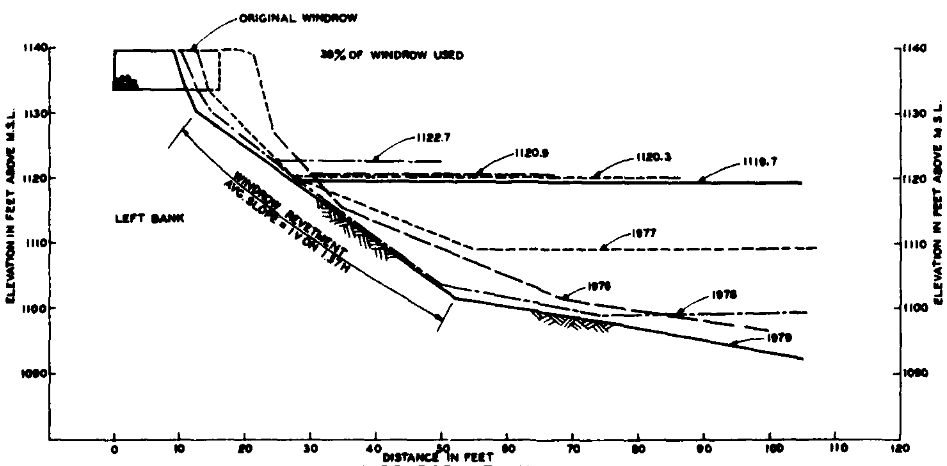
HYDROGRAPH RANGE 4 (SEE NOTE 2)





HYDROGRAPH RANGE 5

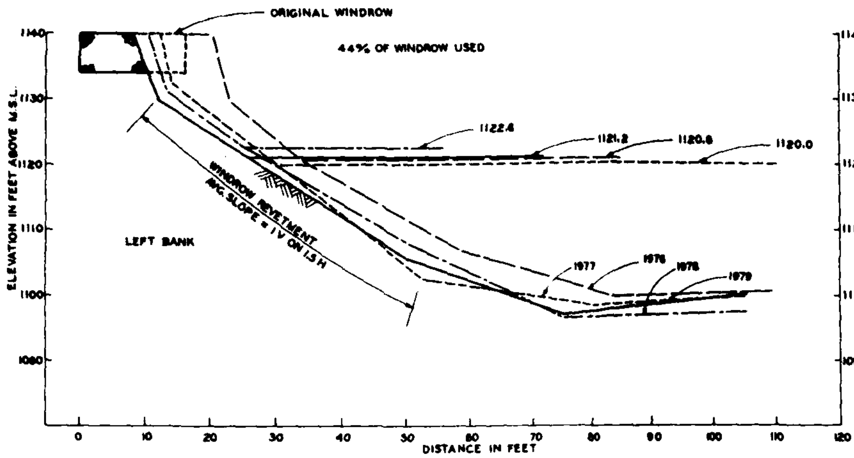




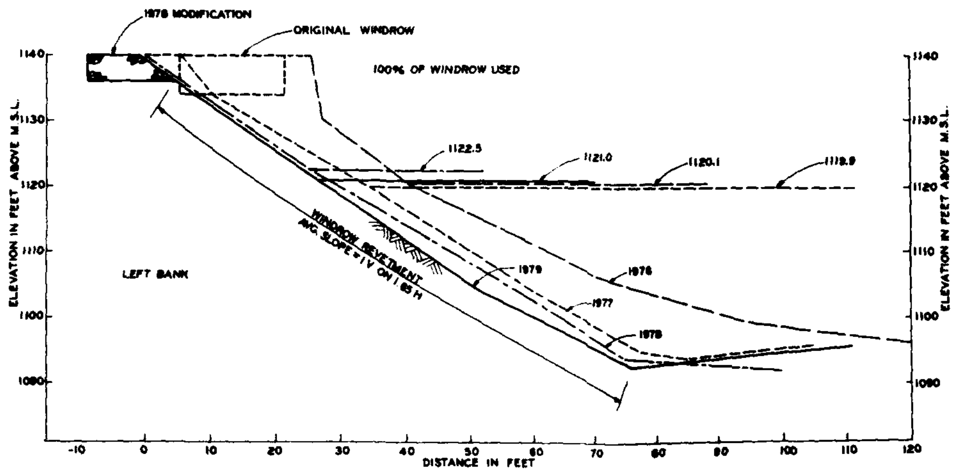
HYDROGRAPH RANGE 6

LEGEND

SYMBOL	DATE	DISCHARGE
	1976	31,228
	1977	26,160
	1978	37,150
	1979	26,105



HYDROGRAPH RANGE 7



HYDROGRAPH RANGE 8

THIS DRAWING HAS BEEN REDUCED TO THREE-EIGHTHS THE ORIGINAL SCALE.

LEGEND

SYMBOL	DATE	DISCHARGE (SEE NOTE 3)
— — —	1976	31,226
- - - - -	1977	28,180
—·—·—	1978	37,150
———	1979	28,105

NOTES:

1. LITTLE CHANGE HAS OCCURRED IN THE BANK CONFIGURATIONS FROM 1978 TO 1979.
2. HYDROGRAPH RANGE LOCATIONS ARE SHOWN ON PLATE 2.
3. THESE VALUES WERE MEASURED IN THE LEFT CHANNEL ALONG THE STUDY REACH DURING THE RESPECTIVE SURVEYS.

MISSOURI RIVER
SECTION 32 STREAMBANK EROSION CONTROL
BANK PROTECTION USING WINDROW REVETMENT
LEFT BANK CONFIGURATION TRENDS
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS, OMAHA, NEBRASKA
JAN. 1980

SCALE: VERT. 1 INCH = 10 FEET
HORIZ. 1 INCH = 10 FEET

PLATE

7